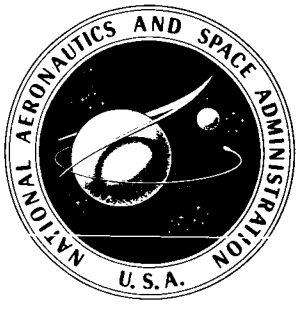
NASA SP-3021

EQUILIBRIUM THERMODYNAMIC PROPERTIES OF THREE ENGINEERING MODELS OF THE MARTIAN ATMOSPHERE

BAILEY



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-3021

EQUILIBRIUM THERMODYNAMIC PROPERTIES OF THREE ENGINEERING MODELS OF THE MARTIAN ATMOSPHERE

By Harry E. Bailey

Ames Research Center
Moffett Field, California

Scientific and Technical Information Division
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
1965
Washington, D.C.

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $2.50

SUMMARY

Entropy, enthalpy, pressure, and sound speed of three carbon dioxide-nitrogen mixtures are presented graphically for wide ranges of temperature and density. The temperature range is 250° K $\leq T \leq 25,000^{\circ}$ K ($\Delta T = 250^{\circ}$ K). The density range is $-7.0 \leq \log \rho/\rho_0 \leq +3.0$ ($\Delta \log \rho/\rho_0 = 0.2$). The chemical compositions of the three mixtures correspond to those selected as Engineering Models of the Mars Atmosphere in NASA TN D-2525.

INTRODUCTION

Three tentative engineering models of the Martian atmosphere have been proposed in reference 1 for use in entry vehicle design. The equilibrium thermodynamic properties (i.e., entropy, enthalpy, pressure, and sound speed) of these three atmospheres have been computed for wide ranges of temperature and density. The temperature range is 250° K $\leq T \leq 25,000^{\circ}$ K ($\Delta T = 250^{\circ}$ K). The density range is $-7.0 \leq \log \rho/\rho_0 \leq +3.0$ ($\Delta \log \rho/\rho_0 = 0.2$). The chemical compositions of the three mixtures correspond to those selected in reference 1.

The computations are similar to those presented in reference 2 and are based on the following assumptions. The species present in the mixture are CO_2, O_2, CO, O, O^+, O^{++}, C, C^+, C^{++}, e^-, N_2, N, NO, NO^+, CN, N^+, N^{++}. Each species behaves as an ideal gas. The thermodynamic properties of the diatomic species are approximated by the rigid rotator-harmonic oscillator model with constants appropriate to the lowest electronic state. Only the first few excited electronic states are considered.

SYMBOLS

a	speed of sound, cm/sec
a_o	speed of sound at standard temperature and pressure, cm/sec
b_j	constant for each species (eq. (5))
C_i	number of atoms/mole of type i at standard temperature and pressure

c	speed of light, cm/sec
c_j	concentration of the jth species, moles/g
$E_{j\ell}$	energy of the ℓth electronic level of the jth species, cm^{-1}
F_j	Gibb's free energy of the jth species, cal/mole
ΔF_i	change in Gibb's free energy for ith reaction, cal/mole
$g_{j\ell}$	degeneracy of the ℓth electronic level of the jth species
H	total enthalpy (zero enthalpy at zero temperature), cal/mole
H_j	enthalpy of the jth species, cal/mole
h	Planck's constant, erg-sec
h_j^o	energy of formation of the jth species, cal/mole
K_i	equilibrium constant for the ith reaction $(\text{atm cm}^3/\text{mole})^{-\beta_i}$
k	Boltzmann's constant, erg/^oK
L_o	Avogadro's number, molecules/mole
m_{ij}	number of i atoms in jth species
m_j	mass of the jth species, g
(mw)	mass of one mole of gas mixture, g
$(mw)_j$	mass of one mole of jth species, g
n_j	number of atoms in jth species
p	pressure, dyn/cm^2
p_o	pressure of one atmosphere, dyn/cm^2
R	gas constant for cold carbon dioxide (for physical units see table IV)
$\mathfrak{R}$	universal gas constant, cal/mole ^oK
$\mathfrak{R}'$	universal gas constant, atm cm^3/mole ^oK
$\mathfrak{R}''$	universal gas constant, ergs/mole ^oK
S	total entropy, cal/mole ^oK
S_j	entropy of the jth species, cal/mole ^oK

T	temperature, ^{o}K
T_o	standard temperature 273.16^{o} K
x_j	mole fraction of jth species
Z	compressibility factor (moles of mixture per cold mole)
β_i	summation over j of all β_{ij}'s
β_{ij}	difference in the stoichiometric coefficients of the jth species in the ith reaction (coefficient on right side of chemical equation minus coefficient on left side)
γ	isentropic exponent
γ_o	isentropic exponent at standard temperature and pressure
θ_{r_j}	characteristic rotational temperature of the jth species, ^{o}K
$\theta_{v_{jl}}$	characteristic vibrational temperature of the lth mode of the jth species, ^{o}K
ρ	density, g/cm^3
ρ_j	density of the jth species, g/cm^3
ρ_o	density at standard temperature and pressure, g/cm^3

METHOD OF COMPUTATION

The thermodynamic properties of each species are given by the following equations (cf. ref. 3).

For all species except carbon dioxide the free energy is

$$\frac{F_j}{\Re T} = -\left[b_j + \frac{5 + 2(n_j - 1)}{2} \ln T + (n_j - 1)\ln\left(\frac{1}{1 - e^{-\theta_{v_j}/T}}\right) + \ln\left(\frac{\sum_{l=1}^{17} g_{jl} e^{-hcE_{jl}/kT}}{g_{j1=1}}\right)\right] + \frac{h_j^o}{\Re T} \qquad \text{(i)}$$

The free energy of carbon dioxide is

$$\frac{F_{CO_2}}{\Re T} = -\left[b_{CO_2} + \frac{7}{2}\ln T - \sum_{l=1}^{4} \ln\left(1 - e^{-\theta v_{CO_2 l}/T}\right)\right] \tag{2}$$

For all species except carbon dioxide the enthalpy is

$$\frac{H_j}{\Re T} = \left[\frac{5 + 2(n_j - 1)}{2}\right] + \frac{(n_j - 1)(\theta v_j/T)}{e^{\theta v_j/T} - 1} + \frac{1}{\Re'' T}\frac{\sum_{l=1}^{17} hcL_o E_{jl} g_{jl} e^{-hcE_{jl}/kT}}{\sum_{l=1}^{17} g_{jl} e^{-hcE_{jl}/kT}} + \frac{h_j^o}{\Re T} \tag{3}$$

The enthalpy of carbon dioxide is

$$\frac{H_{CO_2}}{\Re T} = \frac{7}{2} + \sum_{l=1}^{4} \frac{\theta v_{CO_2 l}/T}{e^{\theta v_{CO_2 l}/T} - 1} \tag{4}$$

The constant b_j is

$$b_j = \frac{3}{2}\ln\left(\frac{2\pi m_j k}{h^2}\right) + \ln\left(\frac{k}{p_o}\right) - (n_j - 1)\ln\theta r_j + \ln g_{jl=1} \tag{5}$$

The entropy is

$$\frac{S_j}{\Re} = \frac{H_j - F_j}{\Re T} \tag{6}$$

The pressure is

$$p_j = \frac{\rho_j \Re' T}{(mw)_j} \tag{7}$$

The values of the physical constants used in the above equations are tabulated in tables I, II, and III.

The thermodynamic properties of the mixture may be found from those of the individual species, according to the equations,

$$p = \sum_{j=1}^{17} p_j \tag{8}$$

$$\frac{H}{RT_o} = Z \sum_{j=1}^{17} x_j \frac{H_j}{\Re T} \frac{T}{T_o} \tag{9}$$

$$\frac{S}{R} = Z \sum_{j=1}^{17} x_j \left[\frac{S_j}{\Re} - \ln \left(\frac{p_j}{p_o} \right) \right] \tag{10}$$

$$x_j = \frac{c_j}{\sum_{i=1}^{17} c_j} \tag{11}$$

The c_j's in the above equations must be determined with the help of the chemical reaction equations and their associated equilibrium constants. In principle, any set of chemical reaction equations which contain each species at least once may be solved for the c_j's. In practice, it is best to select a set of chemical reaction equations which are ordered according to reaction energies. The set used in these calculations is shown below.

CHEMICAL REACTIONS

$2CO_2 = 2CO + O_2$	$O = O^+ + e^-$	$N_2 = N + N$
$CO = C + O$	$O^+ = O^{++} + e^-$	$CN = C + N$
$O_2 = O + O$	$C = C^+ + e^-$	$NO = N + O$
	$C^+ = C^{++} + e^-$	$NO = NO^+ + e^-$
		$N = N^+ + e^-$
		$N^+ = N^{++} + e^-$

No matter what set is selected, the equilibrium constants, K_i, may be evaluated from the free energies of the constituent species and the following equations:

$$\frac{\Delta F_i}{\Re T} = \sum_{j=1}^{17} \beta_{ij} \frac{F_j}{\Re T} \tag{12}$$

$$K_i = (\mathcal{R}'T)^{-\beta_i} e^{-\Delta F_i/\mathcal{R}T} \tag{13}$$

$$\beta_i = \sum_{j=1}^{17} \beta_{ij} \tag{14}$$

$$K_i = \rho^{\beta_i} \prod_{j=1}^{17} c_j^{\beta_{ij}} \tag{15}$$

Four additional equations which insure the conservation of the basic species N, C, O, and e^- are necessary.

$$\sum_{j=1}^{17} m_{ij} c_j = C_i \tag{16}$$

The term m_{ij} is the number of i particles contained in the jth species. The term C_i is the mass fraction of the ith species in the mixture at some reference state (e.g., standard temperature and pressure).

The speed of sound has been evaluated by numerical differentiation of the thermodynamic data. The basic equation defining the speed of sound is

$$a^2 = \left.\frac{\partial p}{\partial \rho}\right|_S \tag{17}$$

Since the numerical data do not contain pressure as a function of density with entropy as a parameter, it is necessary to expand equation (17) to give

$$a^2 = \left.\frac{\partial p}{\partial \rho}\right|_T - \left.\frac{\partial p}{\partial T}\right|_\rho \left[\frac{(\partial S/\partial \rho)|_T}{(\partial S/\partial T)|_\rho}\right] \tag{18}$$

This equation contains only partial derivatives with respect to T and ρ, which are the independent variables in the present computations. All four of the partial derivatives in equation (18) were evaluated numerically.

The compressibility is given by

$$Z = \frac{p(mw)}{\rho \mathcal{R} T} \tag{19}$$

The isentropic exponent is given by

$$\gamma = \frac{a^2 \rho}{p} \tag{20}$$

RESULTS

The results are presented in three sections, one section for each of the three mixtures. The first section, composed of figures 1 through 9, contains the thermodynamic data for a mixture of 4.9-percent carbon dioxide and 95.1-percent nitrogen. The second section, composed of figures 10 through 18, contains the thermodynamic data for a mixture of 10.8-percent carbon dioxide and 89.2-percent nitrogen. The third section, composed of figures 19 through 27, contains the thermodynamic data for a mixture of 48.8-percent carbon dioxide and 51.2-percent nitrogen.

Each section contains first, a key to the regions into which the data is subdivided; second, the detailed data in each region; third, the chemical composition as a function of temperature and density; and fourth, the pressure, enthalpy, entropy, speed of sound, compressibility factor, and isentropic exponent as functions of temperatures.

The values of gas constant, as well as the density, and the speed of sound at standard temperature and pressure are shown in tables IV in several systems of physical unit to facilitate the use of the charts.

DISCUSSION

The assumptions made in these calculations are not uniformly valid over the entire ranges of temperature and density. At the highest densities the assumption that each species behaves individually as an ideal gas is bad. At the highest temperatures, above, say 15,000° K, an insufficient number of the higher electronic energy levels may have been included. In the medium temperature range the rigid rotator-harmonic oscillator approximation based on the lowest electronic level of the molecule will introduce an error.

The errors mentioned in the preceding paragraph may appreciably influence the values of the mole fractions. For over-all thermodynamic variables these errors are less serious.

REFERENCES

1. Levin, G. M.; Evans, D. E.; and Stevens, V.: NASA Engineering Models of the Mars Atmosphere for Entry Vehicle Design. NASA TN D-2525, 1964.

2. Bailey, H. E.: Equilibrium Thermodynamic Properties of Carbon Dioxide. NASA SP-3014, 1965.

3. Marrone, P. V.: Inviscid, Nonequilibrium Flow Behind Bow and Normal Shock Waves. Part I. General Analysis and Numerical Examples. CAL Rep. QM-1626-A-12(I), May 1963.

4. Raymond, J. L.: Thermodynamic Properties of Carbon Dioxide to 24000^{o} K With Possible Application to the Atmosphere of Venus. RM 2292, Rand. Rep., Nov. 1958.

5. Herzberg, Gerhard: Molecular Spectra and Molecular Structure. I. Spectra of Diatomic Molecules. Second ed., D. Von Nostrand Co., Inc., New York, 1950.

6. Herzberg, Gerhard: Molecular Spectra and Molecular Structure. II. Infrared and Raman Spectra of Polyatomic Molecules. Second ed., D. Von Nostrand Co., Inc., New York, 1945.

7. Moore, Charlotte E.: Atomic Energy Levels as Derived From the Analyses of Optical Spectra. NBS Circular 467, U. S. Dept. Com., Natl. Bureau of Standards, Washington, 1949.

TABLE I. - FUNDAMENTAL PHYSICAL CONSTANTS

Universal gas constant:

$\mathfrak{R} = 1.98647$ cal/mole ^{o}K

$\mathfrak{R}' = 82.0561$ atm cm^3/mole ^{o}K

$\mathfrak{R}'' = 8.3134 \times 10^{7}$ erg/mole ^{o}K

Planck's constant:

$h = 6.6256 \times 10^{-27}$ erg-sec

Boltzmann's constant:

$k = 1.38054 \times 10^{-16}$ erg/^{o}K

Pressure of one atmosphere:

$p_o = 1.013 \times 10^{6}$ dyn/cm^2

Avogadro's number:

$L_o = 6.02252 \times 10^{23}$ molecules/mole

Speed of light:

$c = 2.99793 \times 10^{10}$ cm/sec

TABLE II. - ATOMIC CONSTANTS USED IN PROGRAM

Species	n_j	$(mw)_j$	b_j	θ_{v_j}, °K	θ_{r_j}, °K	h_j^o, kcal/mole
O_2	2	32.000(3)[a]	1.21618(3)	2256(3)	4.16(3)	93.964(4)
O	1	16.000(3)	2.1032(3)	---	---	105.96(4)
O^+	1	16.000(3)	1.8794(3)	---	---	419.88(4)
O^{++}	1	16.000	.4939	---	---	1230.5(4)
e^-	1	5.4847×10^{-4}(3)	-14.23517(3)	---	---	0
CO_2	---	44.011	1.8948	1932.1(6) 960.1 960.1 3380.0	1.124(6)	0
CO	2	28.011	.3118	3082(5)	2.779	19.782(4)
C	1	12.011	.0637	---	---	169.99(4)
C^+	1	12.011	.7569	---	---	429.77(4)
C^{++}	1	12.011	.0637	---	---	991.956(4)
N_2	2	28.014(3)	-.42163(3)	3374(3)	5.78(3)	0
N	1	14.007(3)	1.67997(3)	---	---	112.59(3)
N^+	1	14.007(3)	.29368(3)	---	---	447.7(3)
N^{++}	1	14.007	.9879	---	---	1130.5(7)
NO	2	30.007(3)	1.23256(3)	2719(3)	2.45(3)	68.46
NO^+	2	30.007(3)	.37861(3)	3397(3)	2.88(3)	281.95
CN	2	26.018(5)	.9109	2958	2.733	92.22(5)

[a]Numbers in ( ) refer to references from which the physical constants were taken. Those physical constants without reference numbers were computed for this report.

TABLE III. - ELECTRONIC ENERGY LEVELS

Species	Energy level, cm^{-1}	Degeneracy	Species	Energy level, cm^{-1}	Degeneracy
O_2	0	3	O^{++}	0	1
	7918	2		113.4	3
	13195	1 (3)[a]		306.8	5
	36096	3		20271	5 (7)
	49802	3		43183.5	1
CO	0	1		60312.1	5
	48687.5	6	C	0	1
	55901	3 (5)		16.4	3
	62299.4	6		43.5	5
	65074.8	2		10193.7	5 (7)
O	0	5		21648.4	1
	159	3		33735.2	5
	227	1 (3)	C^+	0	2
	15868	5		64	4
	33792	1		43000.2	2 (7)
O^+	0	4		43021.8	4
	26808	6		43050.7	6
	26829	4 (3)	C^{++}	0	1
	40467	4		52315	1
	40468	2		52338	3 (7)
N_2	0	1		52394.8	5
	50256	3	N	0	4
	59626	6 (3)		19228	6
	60000	1		19281	4 (3)
NO	0	4		28840	4
	121	4		28840	2
	43966	2 (3)	N^+	0	1
	45918	4		49	3
NO^+	0	1		131	5
	20000	3		15316	5 (3)
	31000	6 (3)		32687	1
	36000	6		47168	5
CN	0	2	N^{++}	0	2
	9242	4 (5)		174.5	4
	25752	2		57192.1	2 (7)
				57252.0	4
				57333.2	6

[a] Numbers in ( ) refer to references from which the physical constants were taken.

TABLE IVa. - CONSTANTS FOR MIXTURE OF 4.9-PERCENT CARBON DIOXIDE AND 95.1-PERCENT NITROGEN

Gas constant for mixture:

$$R = 1.726 \times 10^{3} \text{ ft}^2/\text{sec}^2 \ ^{\circ}\text{R}$$

$$R = 2.886 \times 10^{6} \text{ cm}^2/\text{sec}^2 \ ^{\circ}\text{K}$$

$$R = 2.886 \times 10^{2} \text{ m}^2/\text{sec}^2 \ ^{\circ}\text{K}$$

Density at standard temperature and pressure:

$$\rho_o = 0.2493 \times 10^{-2} \text{ slug/ft}^3$$

$$\rho_o = 0.1285 \times 10^{-2} \text{ g/cm}^3$$

$$\rho_o = 0.1285 \times 10^{1} \text{ kg/m}^3$$

Sound speed at standard temperature and pressure:

$$a_o = 1.087 \times 10^{3} \text{ ft/sec}$$

$$a_o = 0.3313 \times 10^{5} \text{ cm/sec}$$

$$a_o = 0.3313 \times 10^{3} \text{ m/sec}$$

Isentropic exponent at standard temperature and pressure:

$$\gamma_o = 1.393$$

Product of gas constant and standard temperature:

$$RT_o = 0.8489 \times 10^{6} \text{ ft}^2/\text{sec}^2$$

$$RT_o = 0.7884 \times 10^{9} \text{ cm}^2/\text{sec}^2$$

$$RT_o = 0.1884 \times 10^{2} \text{ cal/g}$$

$$RT_o = 0.3391 \times 10^{2} \text{ Btu/lbm}$$

$$RT_o = 0.7884 \times 10^{5} \text{ J/kg}$$

Molecular weight of mixture:

$$mw = 28.8 \text{ g/mole}$$

TABLE IVb. - CONSTANTS FOR MIXTURE OF 10.8-PERCENT CARBON DIOXIDE AND 89.2-PERCENT NITROGEN

Gas constant for mixture:

$$R = 1.672 \times 10^{3} \text{ ft}^2/\text{sec}^2 \ ^{\circ}\text{R}$$

$$R = 2.796 \times 10^{6} \text{ cm}^2/\text{ sec}^2 \ ^{\circ}\text{K}$$

$$R = 2.796 \times 10^{2} \text{ m}^2/\text{sec}^2 \ ^{\circ}\text{K}$$

Density at standard temperature and pressure:

$$\rho_o = 0.2574 \times 10^{-2} \text{ slug/ft}^3$$

$$\rho_o = 0.1327 \times 10^{-2} \text{ g/cm}^3$$

$$\rho_o = 0.1327 \times 10^{1} \text{ kg/m}^3$$

Sound speed at standard temperature and pressure:

$$a_o = 1.066 \times 10^{3} \text{ ft/sec}$$

$$a_o = 0.3249 \times 10^{5} \text{ cm/sec}$$

$$a_o = 0.3249 \times 10^{3} \text{ m/sec}$$

Isentropic exponent at standard temperature and pressure:

$$\gamma_o = 1.384$$

Product of gas constant and standard temperature:

$$RT_o = 0.8219 \times 10^{6} \text{ ft}^2/\text{sec}^2$$

$$RT_o = 0.7634 \times 10^{9} \text{ cm}^2/\text{sec}^2$$

$$RT_o = 0.1827 \times 10^{2} \text{ cal/g}$$

$$RT_o = 0.3283 \times 10^{2} \text{ Btu/lbm}$$

$$RT_o = 0.7634 \times 10^{5} \text{ J/kg}$$

Molecular weight of mixture:

$$mw = 29.7 \text{ g/mole}$$

TABLE IVc. - CONSTANTS FOR MIXTURE OF 48.8-PERCENT CARBON DIOXIDE AND 51.2-PERCENT NITROGEN

Gas constant for mixture:

$$R = 1.388 \times 10^{3} \text{ ft}^2/\text{sec}^2 \ ^{\circ}\text{R}$$

$$R = 2.321 \times 10^{6} \text{ cm}^2/\text{sec}^2 \ ^{\circ}\text{K}$$

$$R = 2.321 \times 10^{2} \text{ m}^2/\text{sec}^2 \ ^{\circ}\text{K}$$

Density at standard temperature and pressure:

$$\rho_o = 0.3101 \times 10^{-2} \text{ slug/ft}^3$$

$$\rho_o = 0.1599 \times 10^{-2} \text{ g/cm}^3$$

$$\rho_o = 0.1599 \times 10^{1} \text{ kg/m}^3$$

Sound speed at standard temperature and pressure:

$$a_o = 0.9530 \times 10^{3} \text{ ft/sec}$$

$$a_o = 0.2905 \times 10^{5} \text{ cm/sec}$$

$$a_o = 0.2905 \times 10^{3} \text{ m/sec}$$

Isentropic exponent at standard temperature and pressure:

$$\gamma_o = 1.332$$

Product of gas constant and standard temperature:

$$RT_o = 0.6824 \times 10^{6} \text{ ft}^2/\text{sec}^2$$

$$RT_o = 0.6338 \times 10^{9} \text{ cm}^2/\text{sec}^2$$

$$RT_o = 0.1514 \times 10^{2} \text{ cal/g}$$

$$RT_o = 0.2726 \times 10^{2} \text{ Btu/lbm}$$

$$RT_o = 0.6338 \times 10^{5} \text{ J/kg}$$

Molecular weight of mixture:

$$mw = 35.85 \text{ g/mole}$$

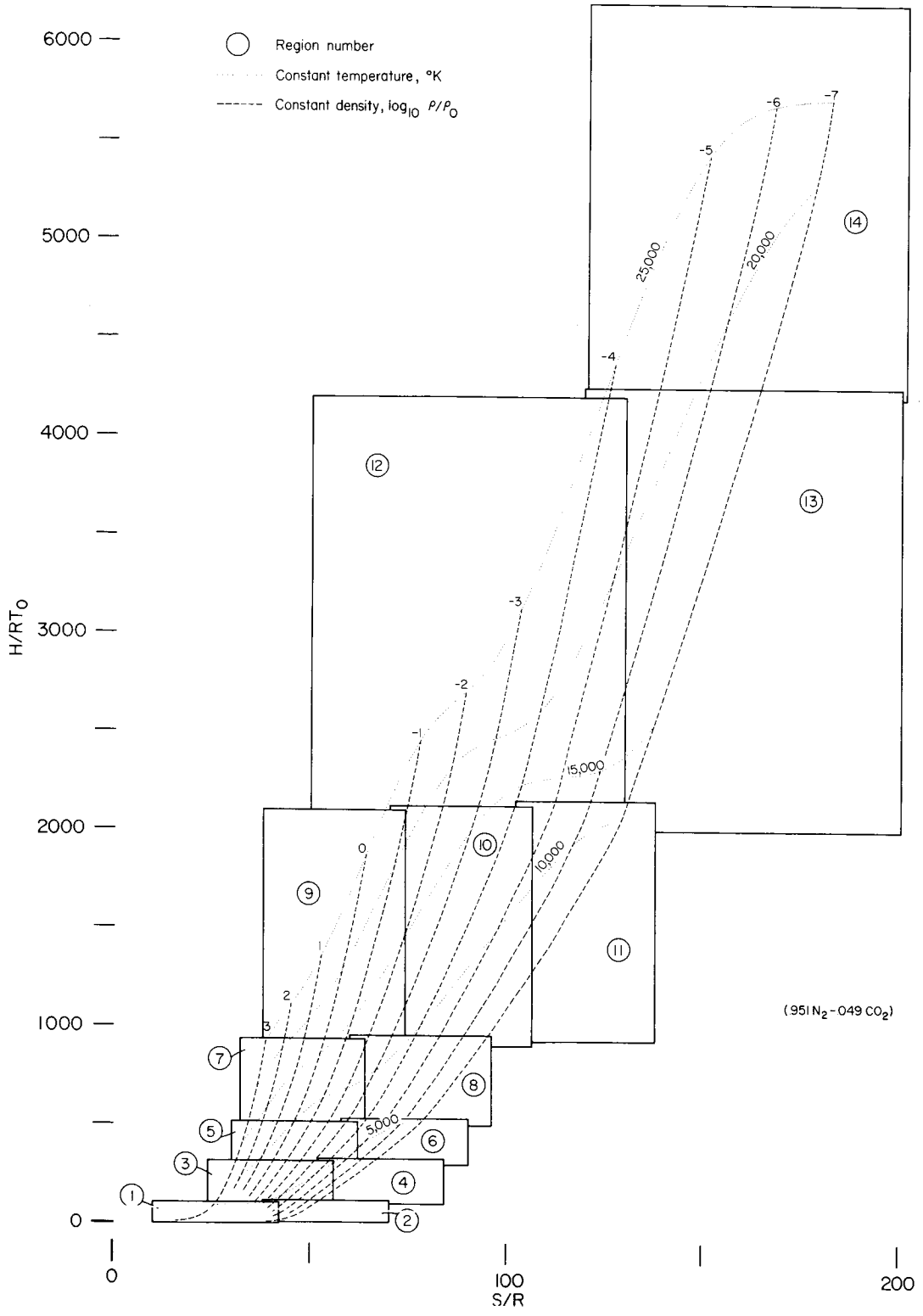
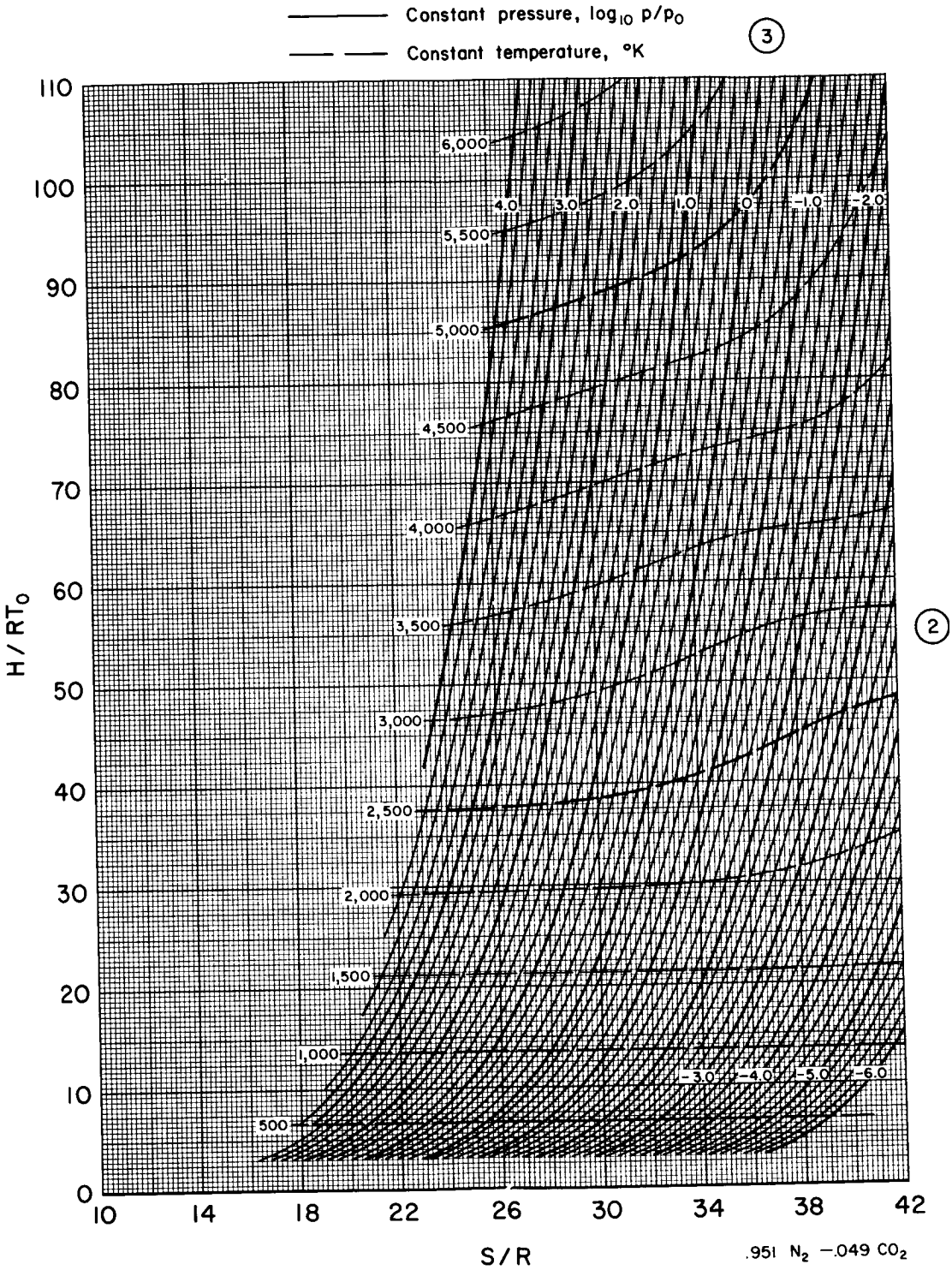
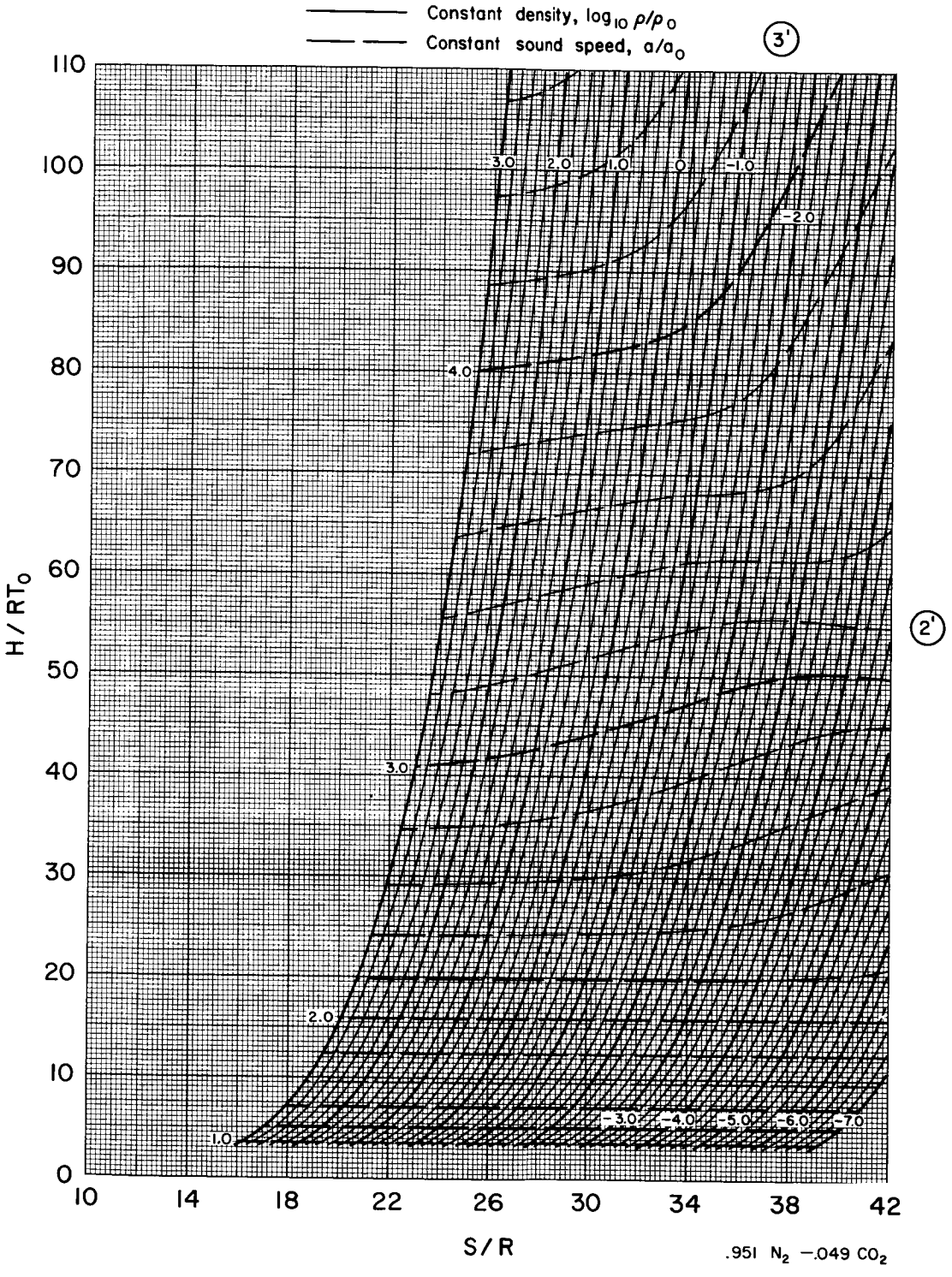


Figure 1. - Key to presentation of thermodynamic data.



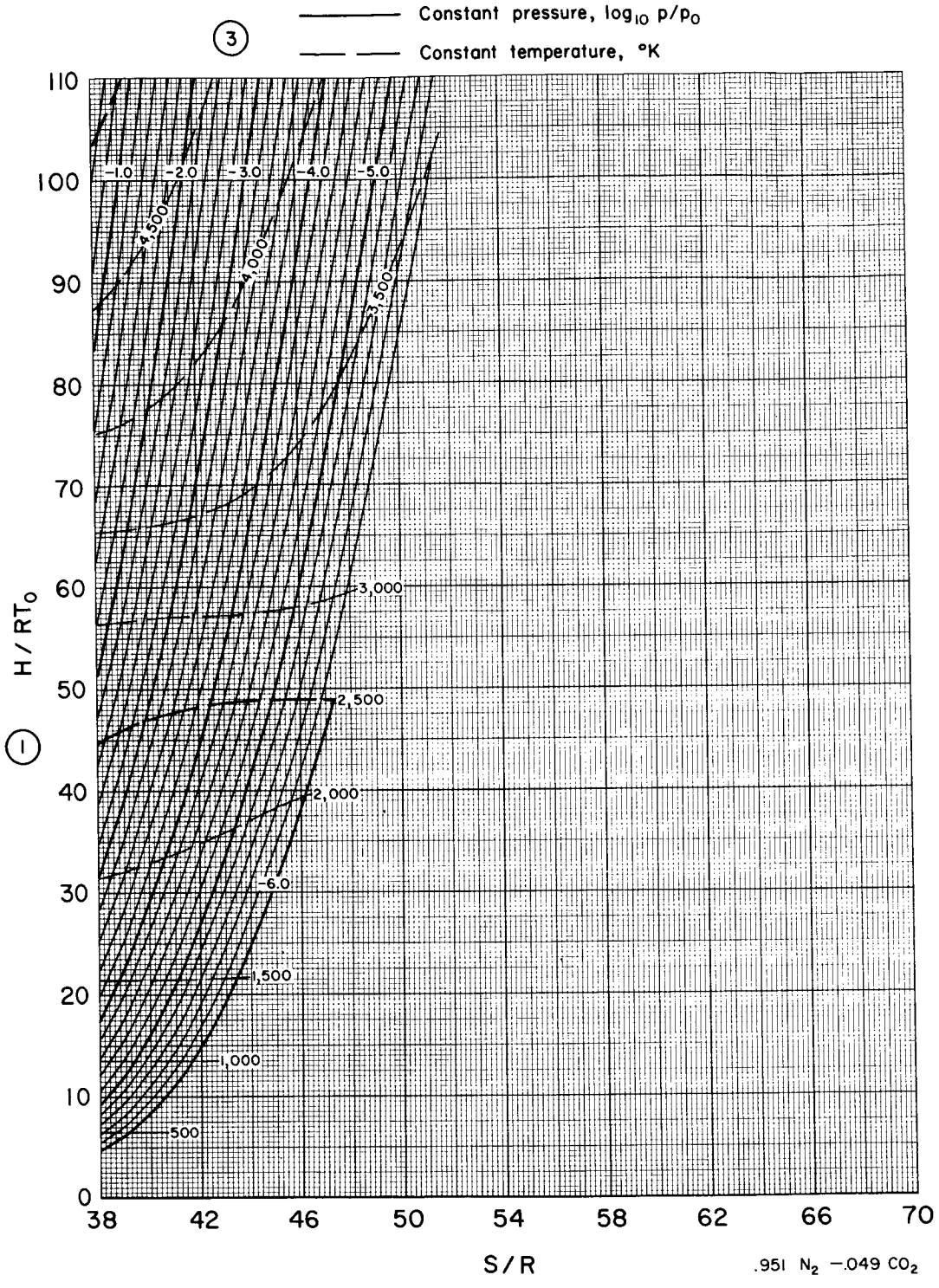
(a) Region 1.

Figure 2. - Thermodynamic data.



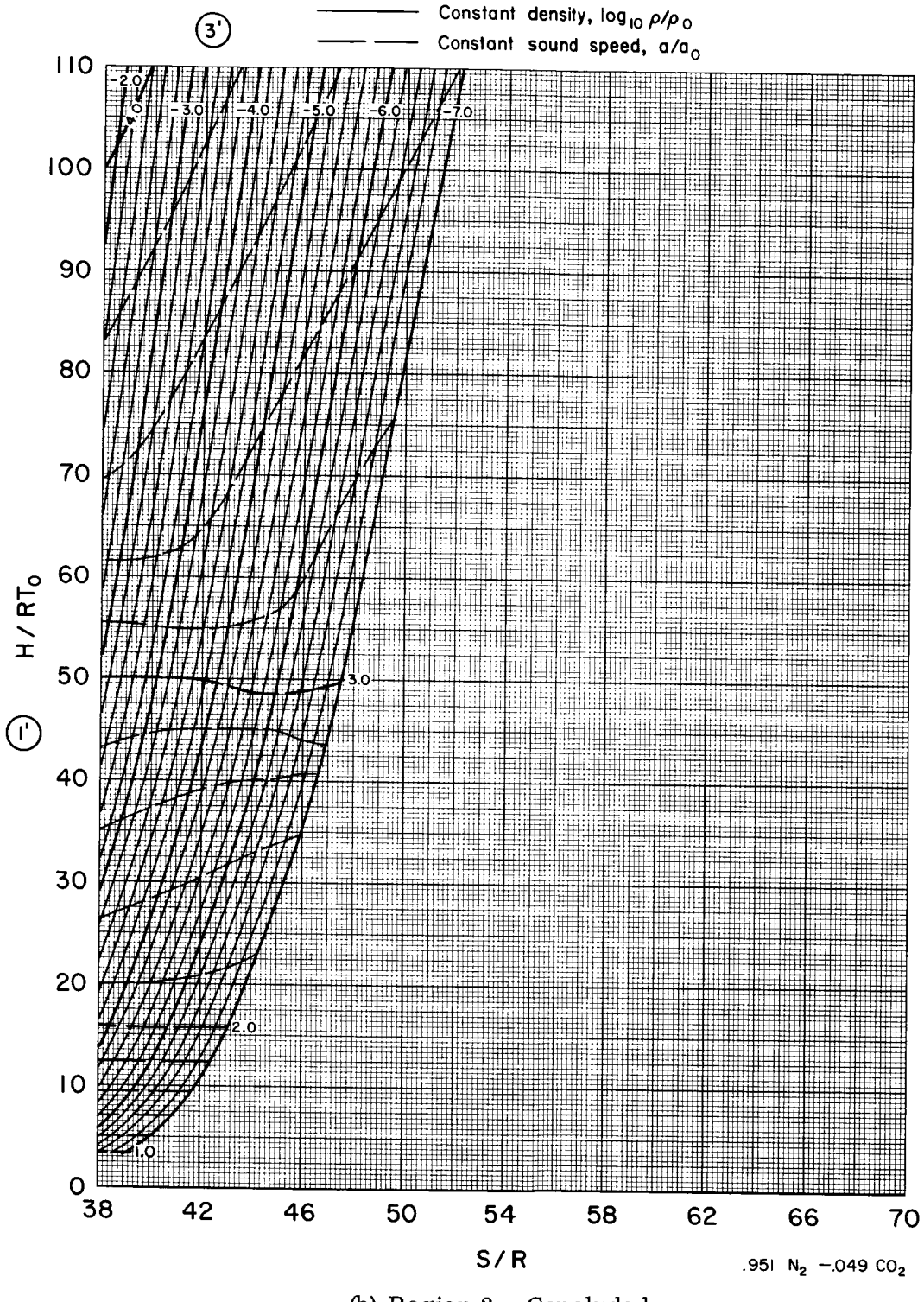
(a) Region 1 - Concluded.

Figure 2. - Continued.



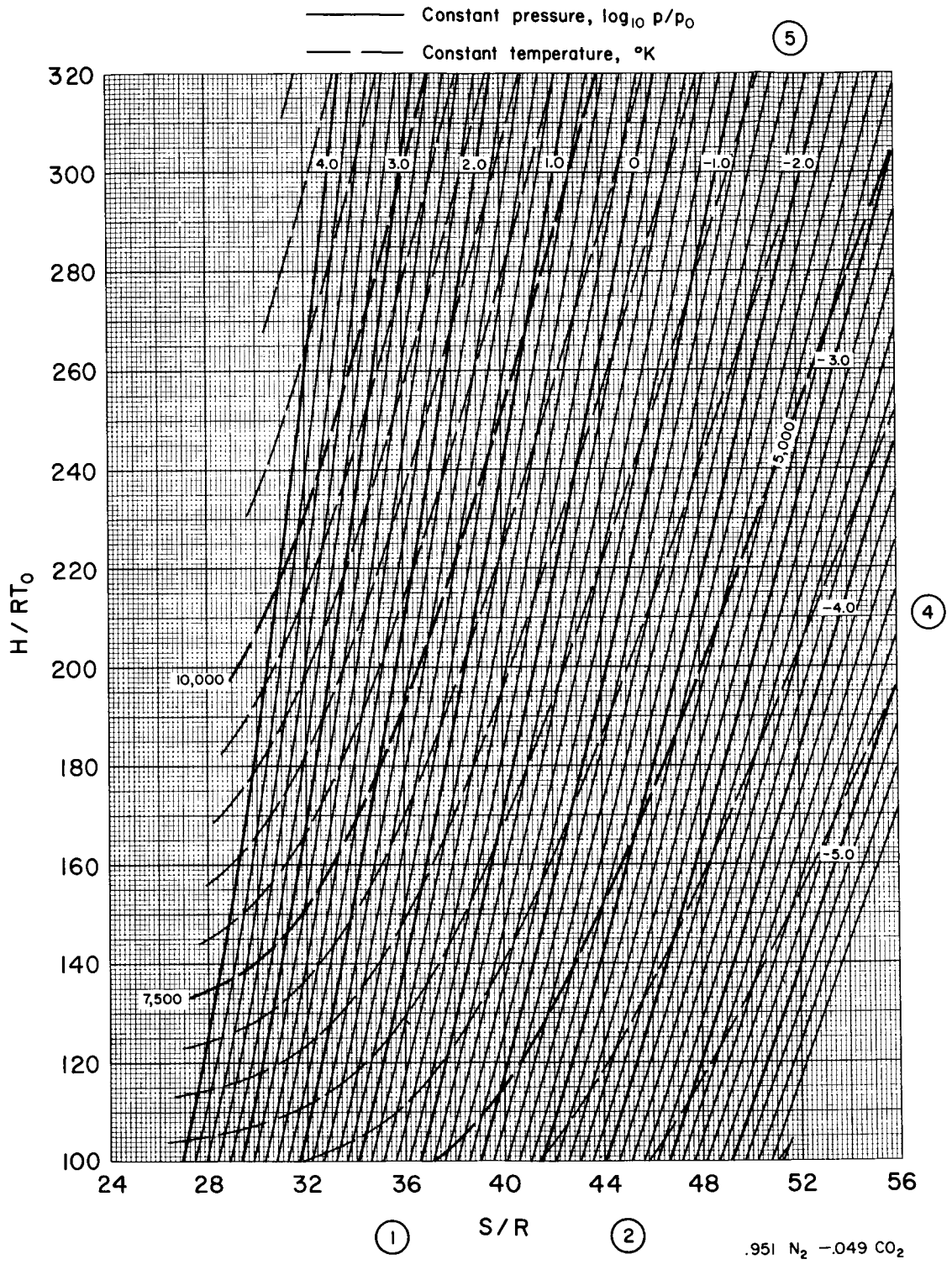
(b) Region 2.

Figure 2. - Continued.



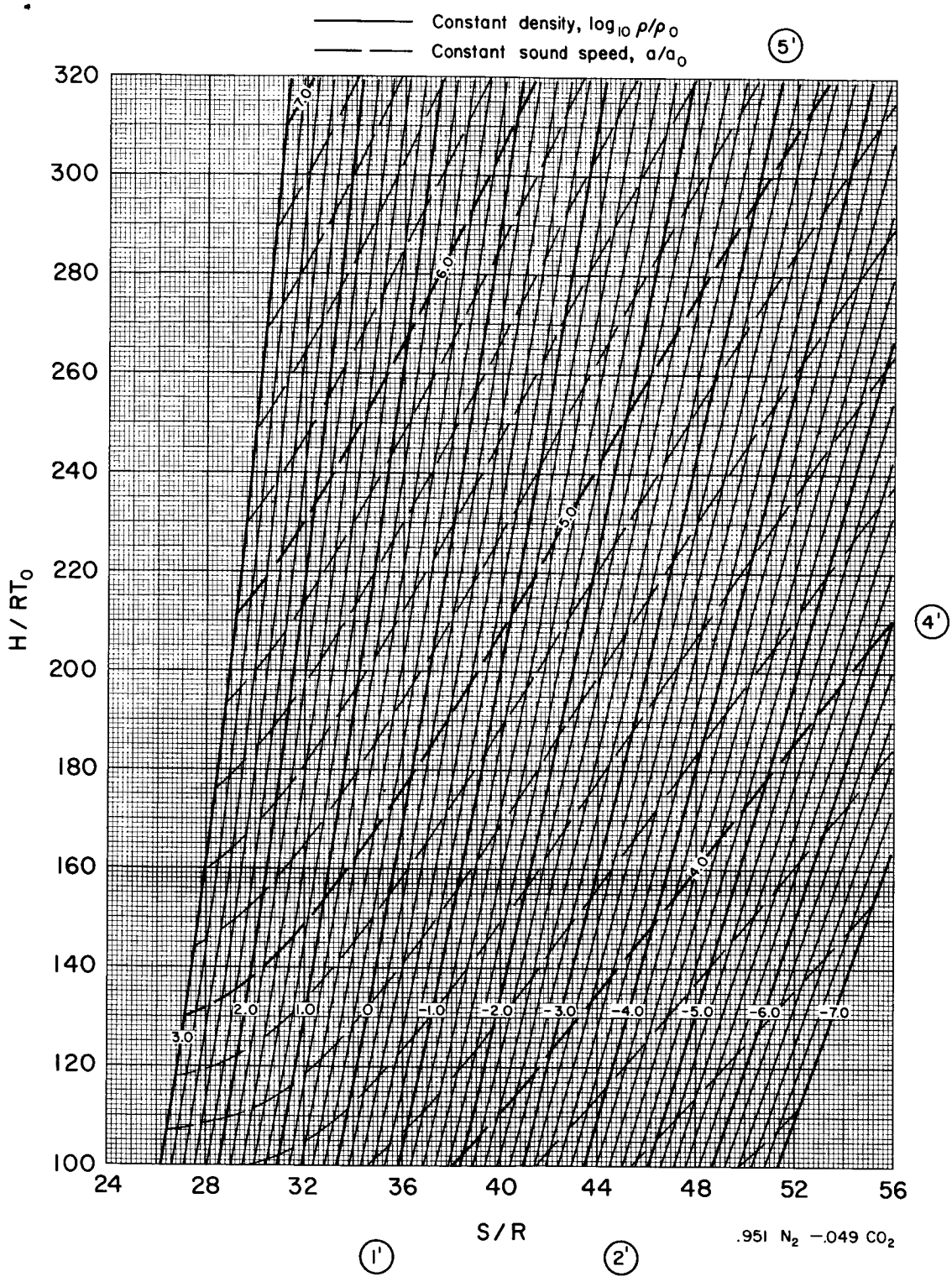
(b) Region 2 - Concluded.

Figure 2. - Continued.



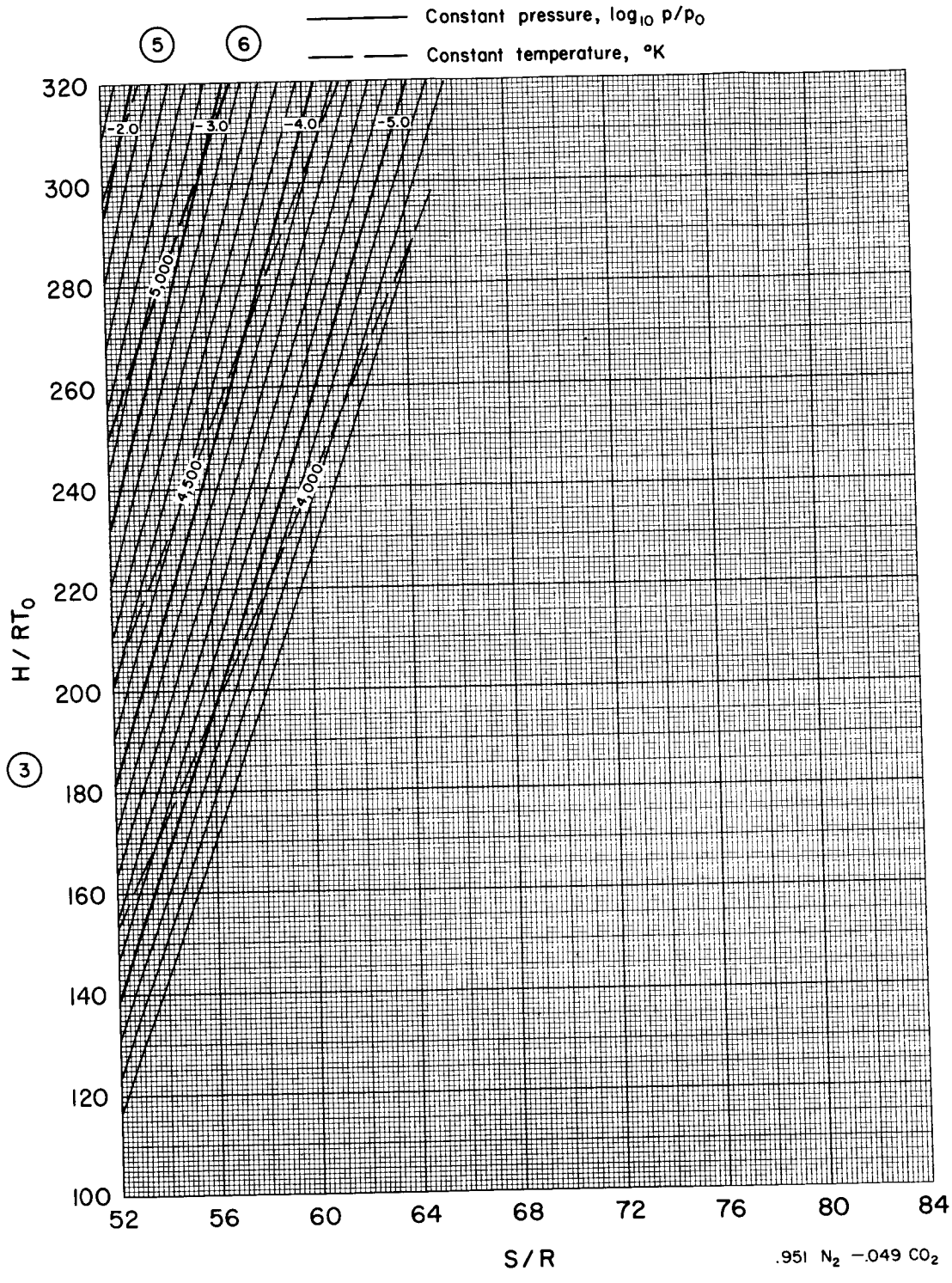
(c) Region 3.

Figure 2. - Continued.



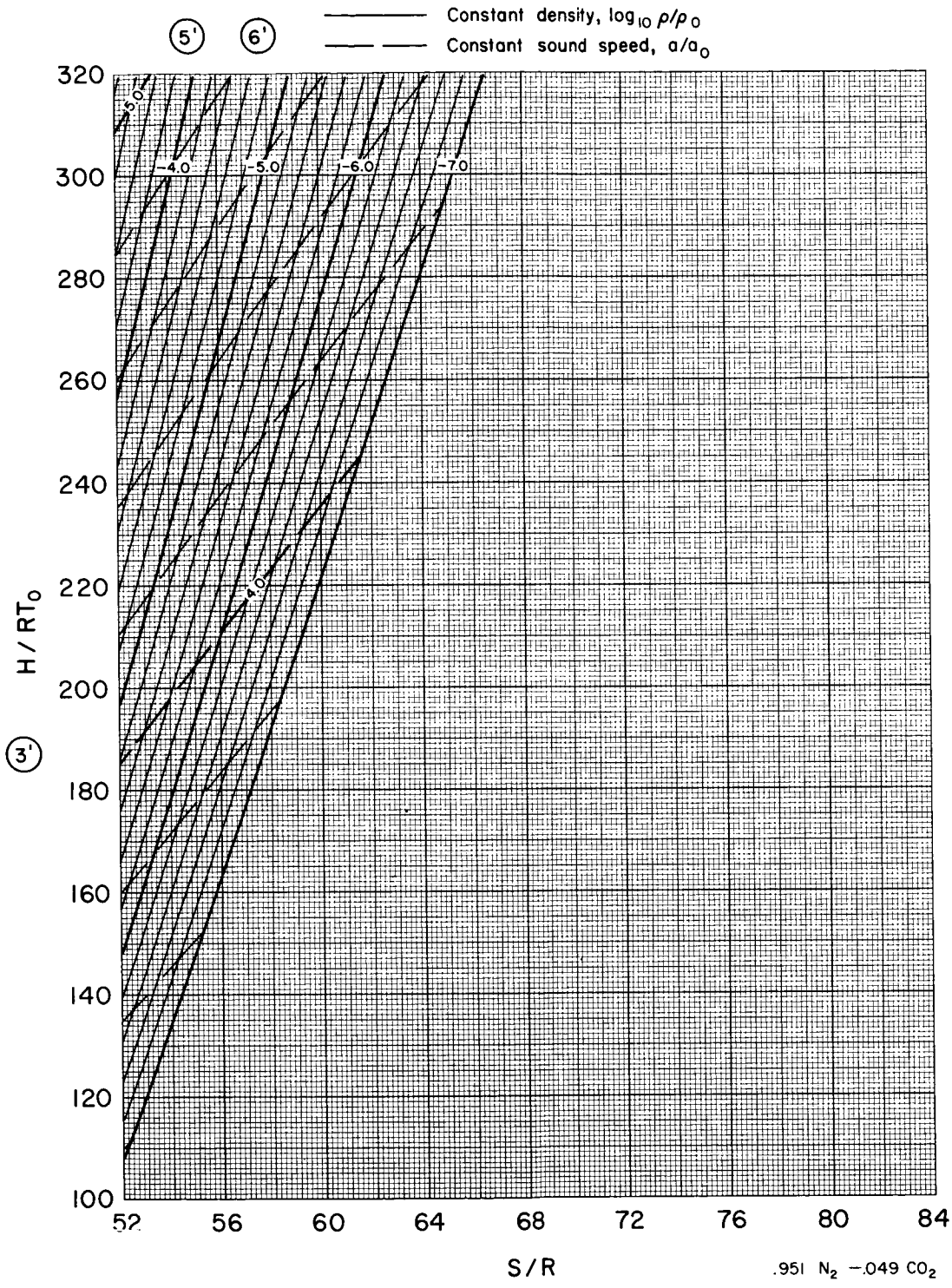
(c) Region 3 - Concluded.

Figure 2. - Continued.



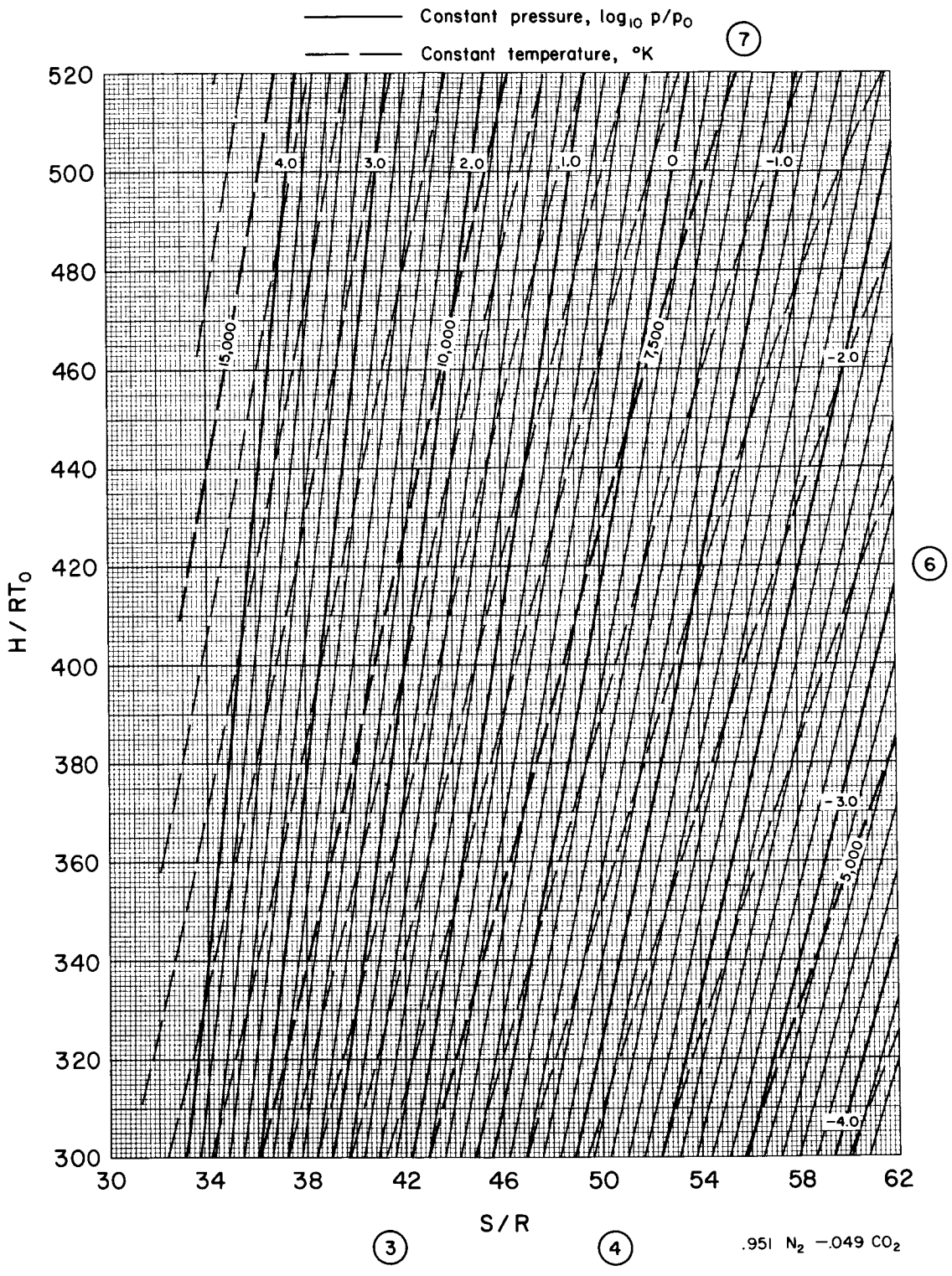
(d) Region 4.

Figure 2. - Continued.



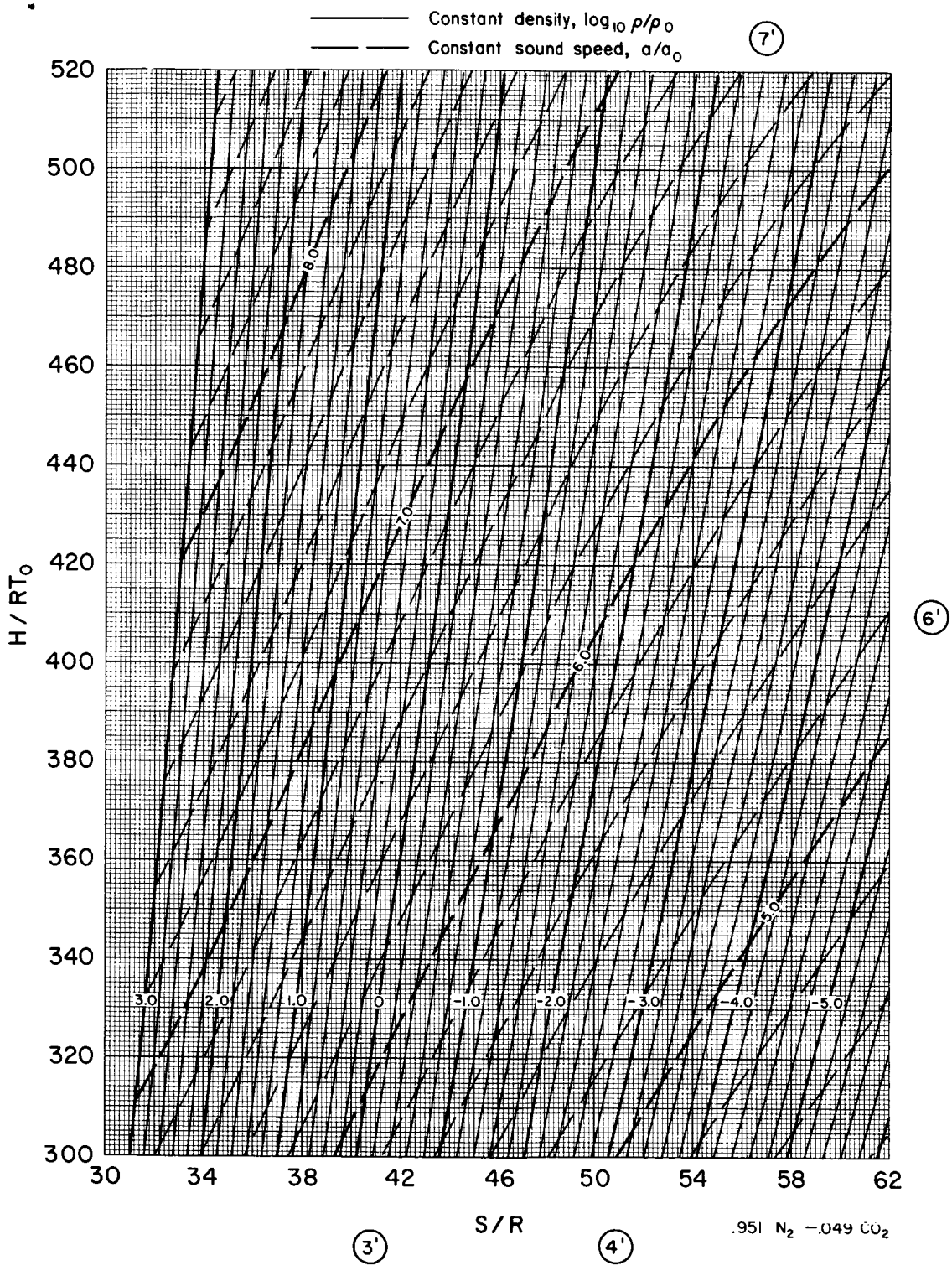
(d) Region 4 - Concluded.

Figure 2. - Continued.



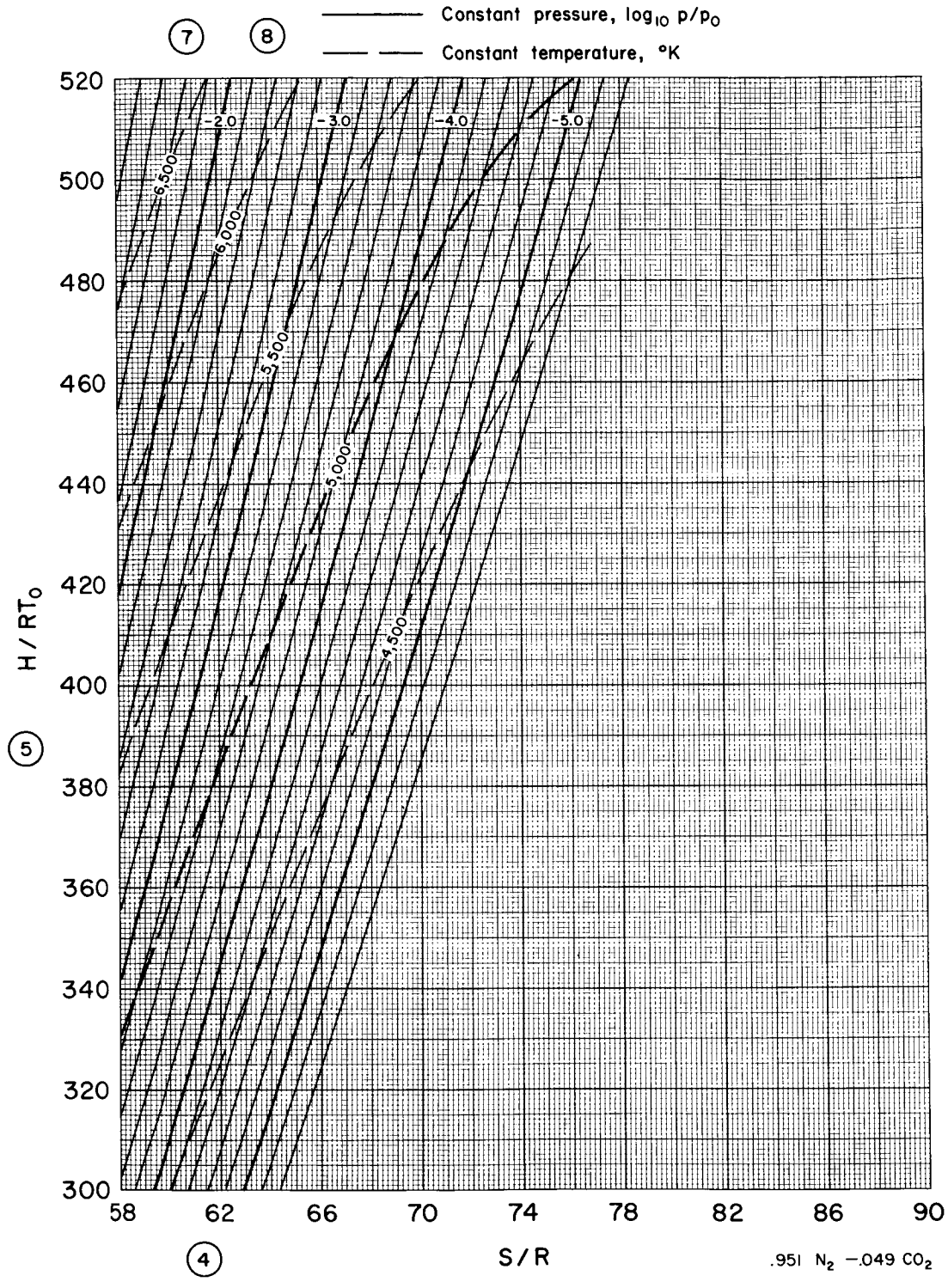
(e) Region 5

Figure 2. - Continued.



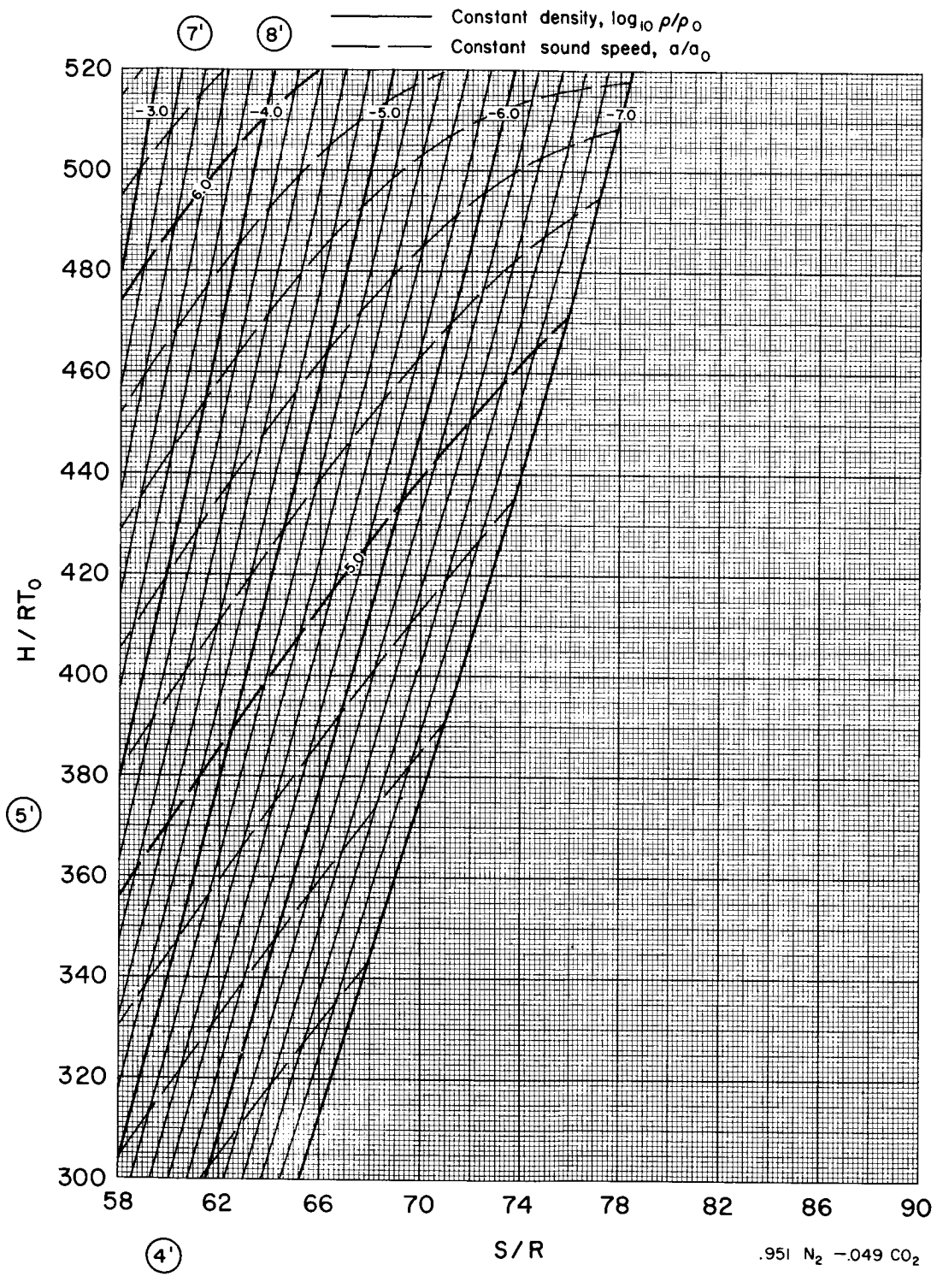
(c) Region 5 - Concluded.

Figure 2. - Continued.



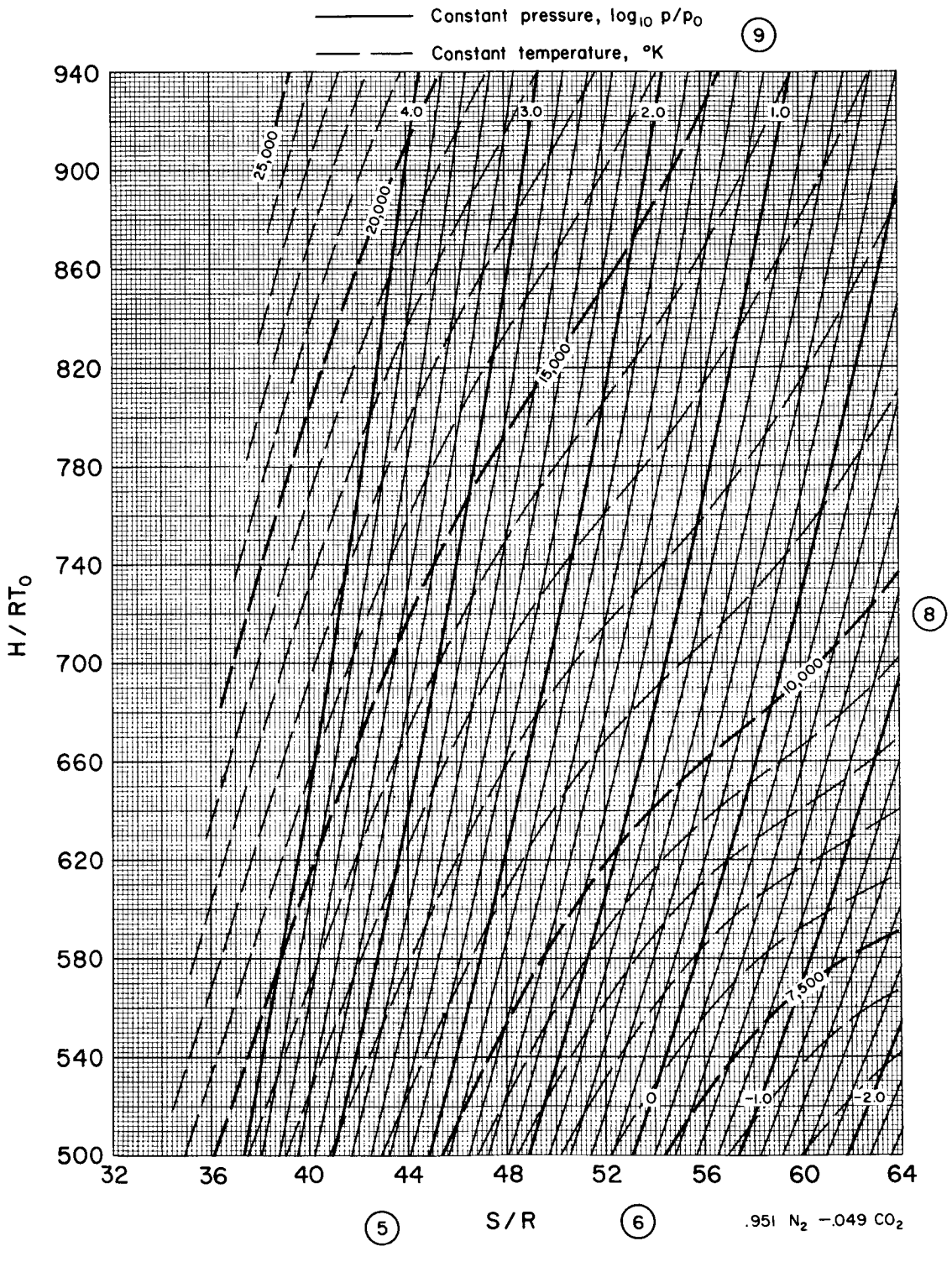
(f) Region 6.

Figure 2. - Continued.



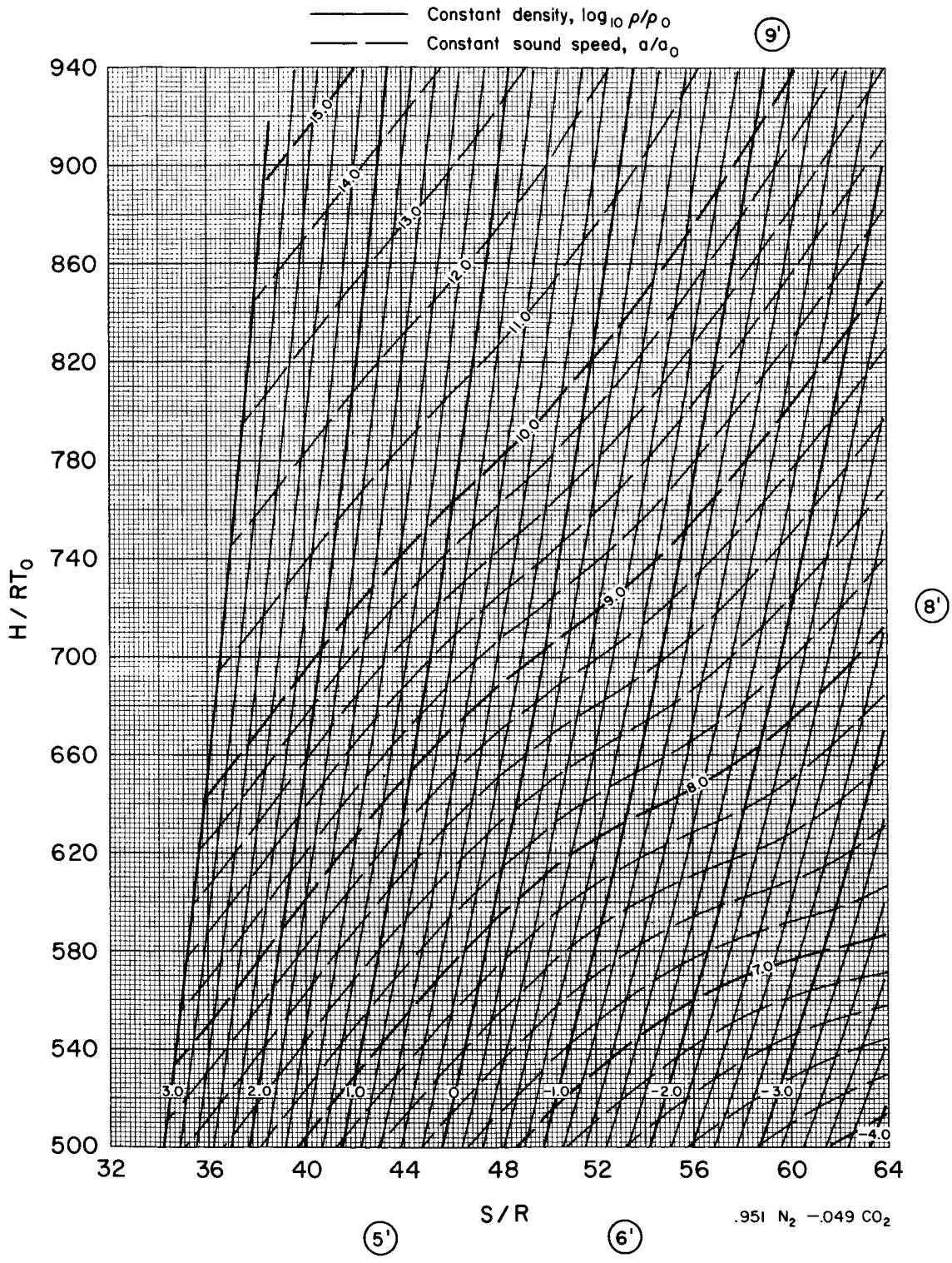
(f) Region 6 - Concluded.

Figure 2. - Continued.



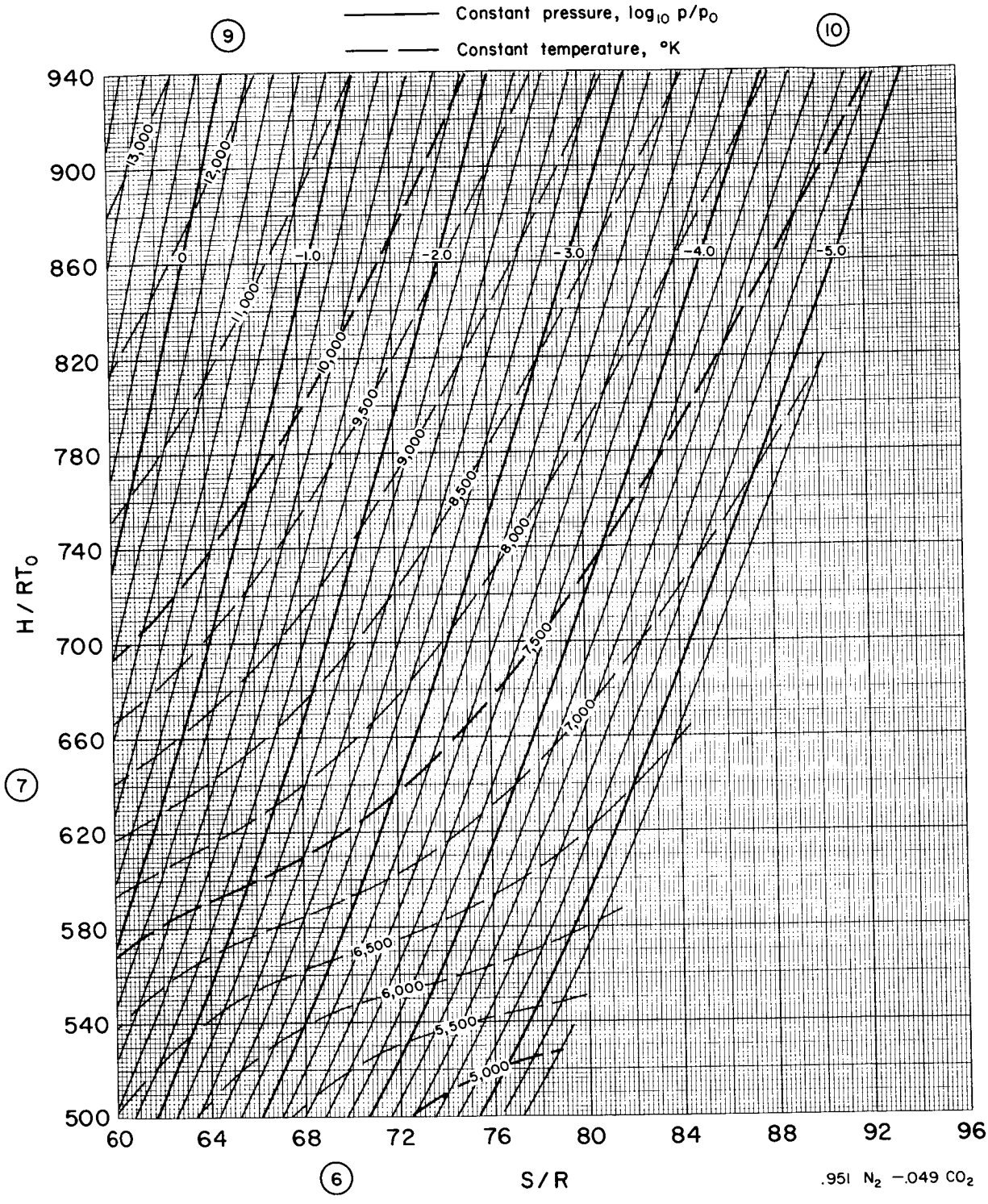
(g) Region 7.

Figure 2. - Continued.



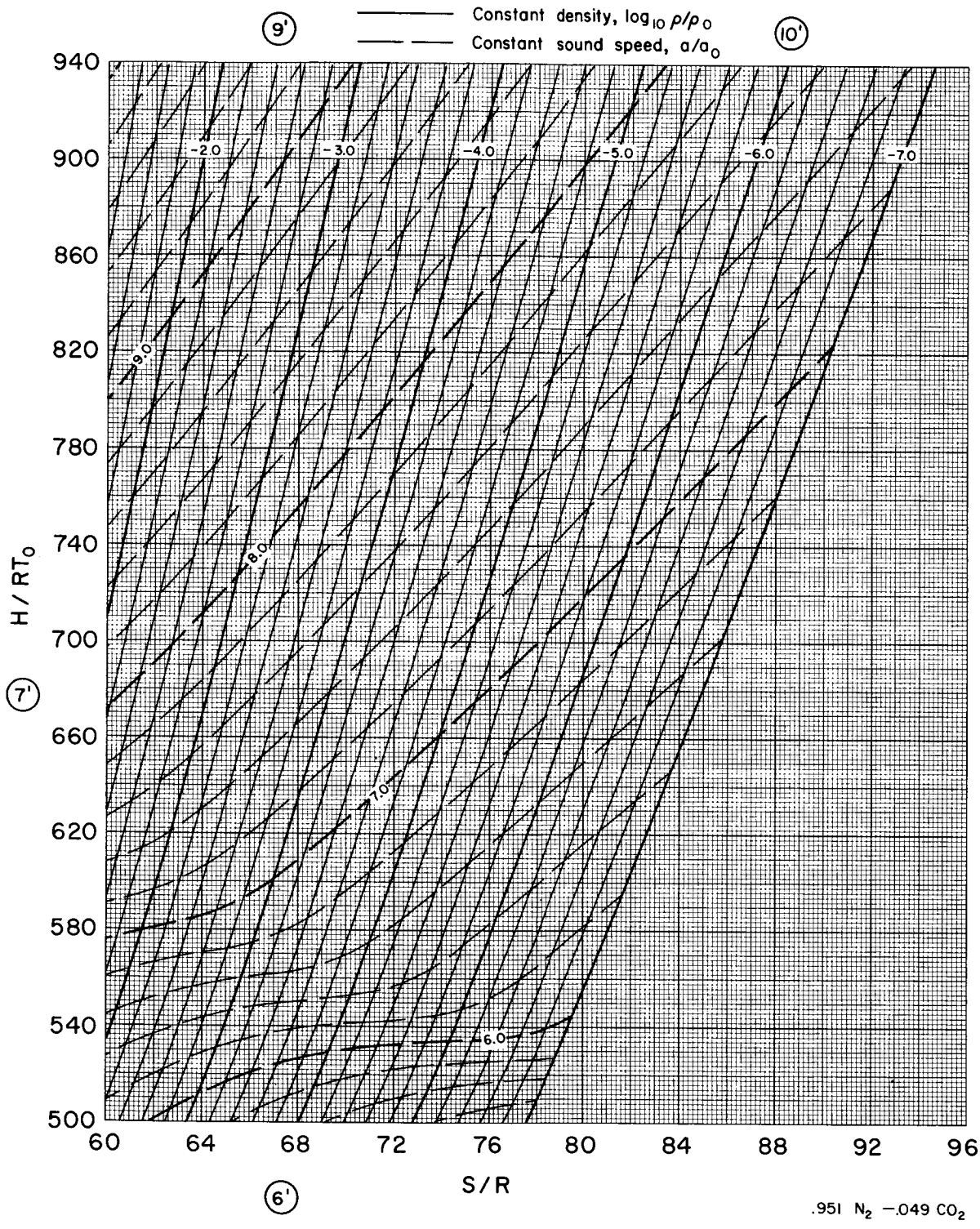
(g) Region 7 - Concluded.

Figure 2. - Continued.



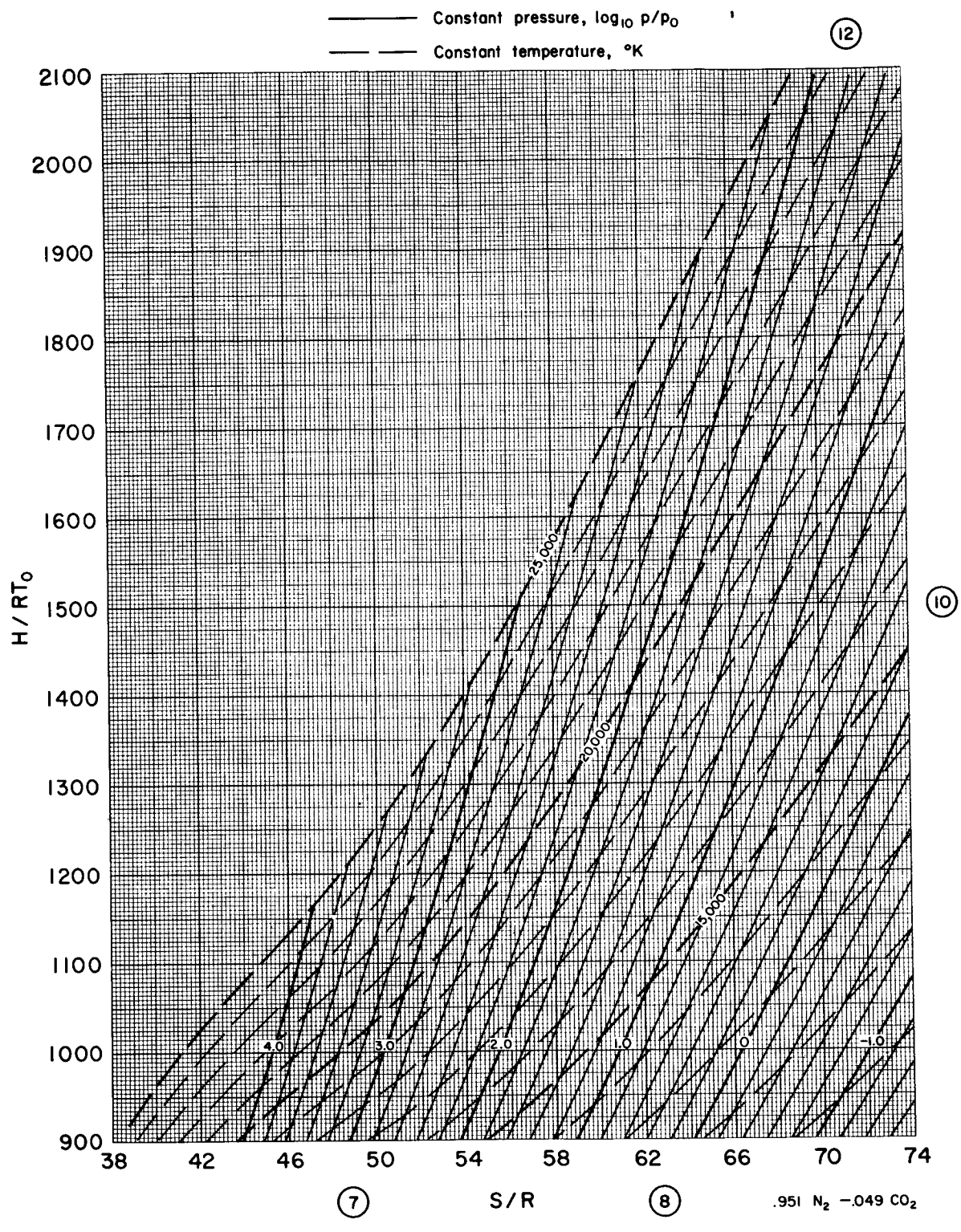
(h) Region 8.

Figure 2. - Continued.



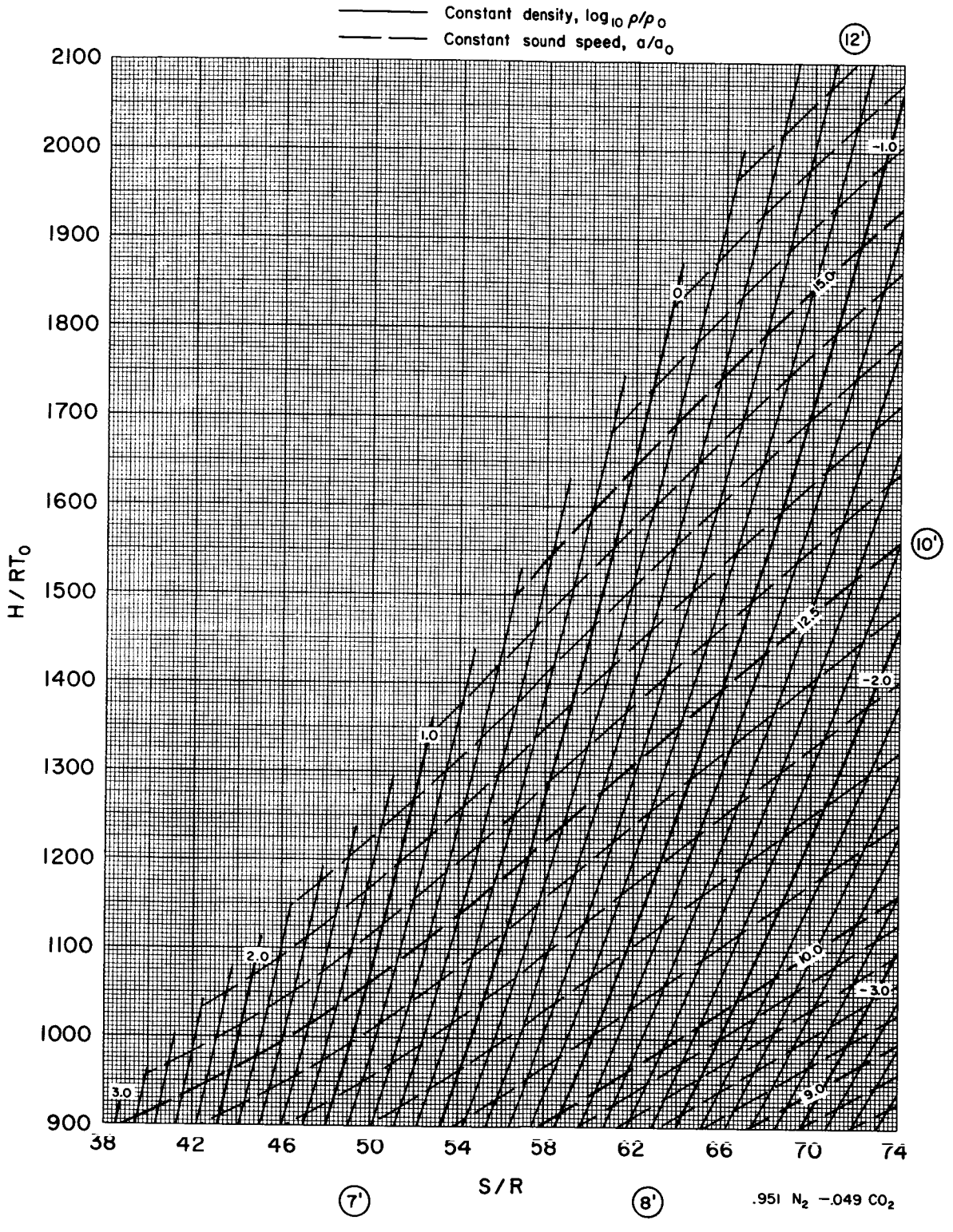
(h) Region 8 - Concluded.

Figure 2. - Continued.



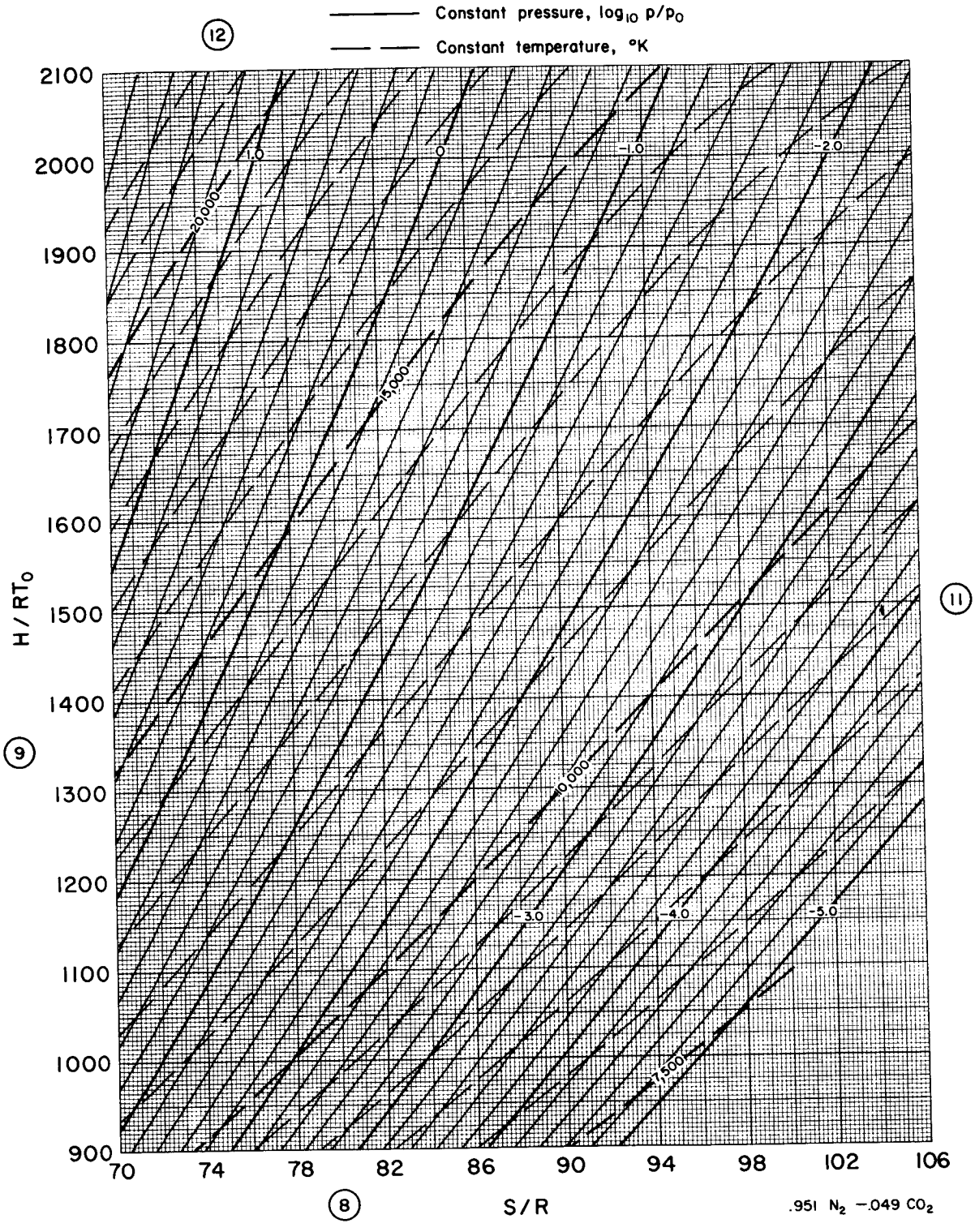
(i) Region 9.

Figure 2. - Continued.



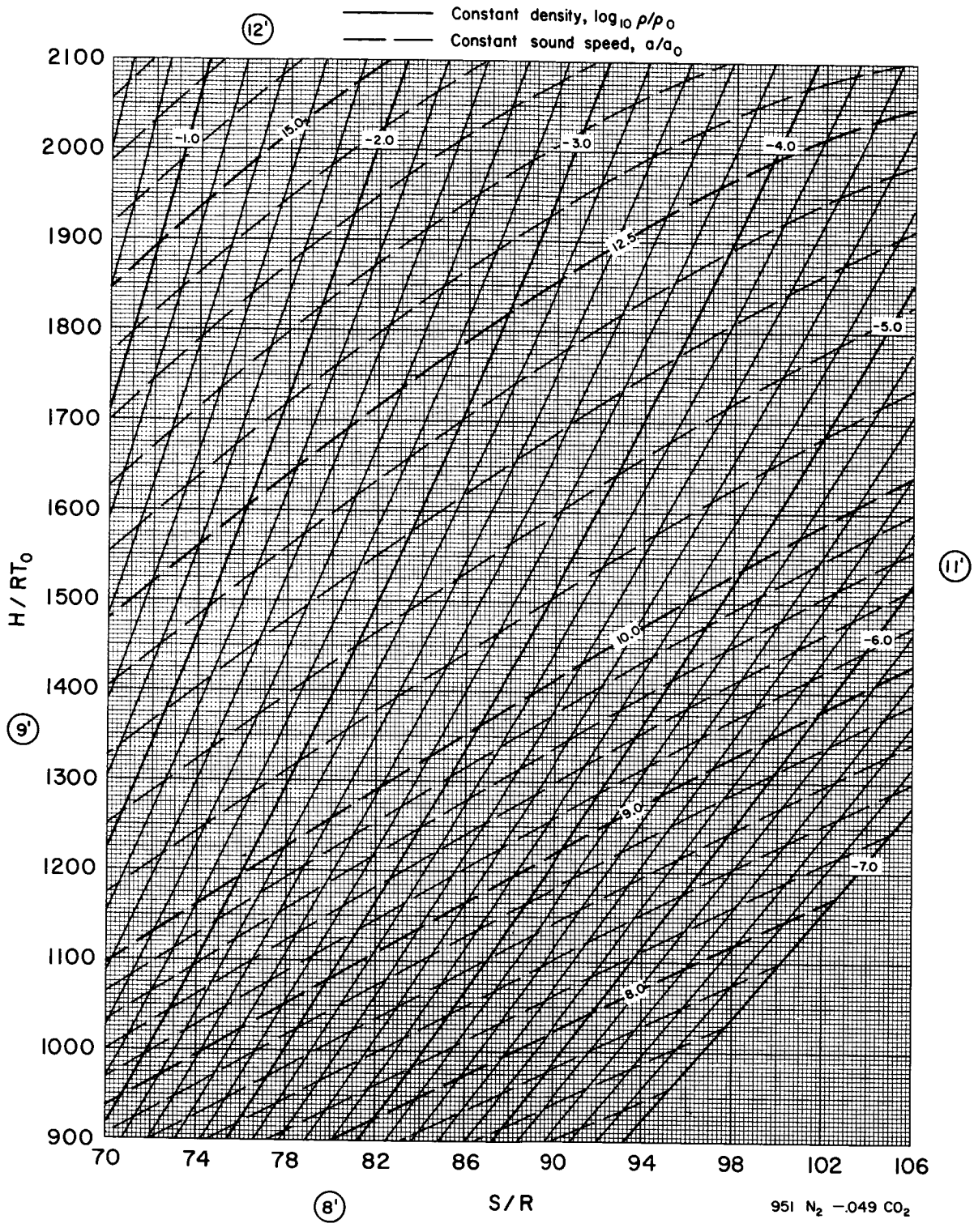
(i) Region 9 - Concluded.

Figure 2. - Continued.



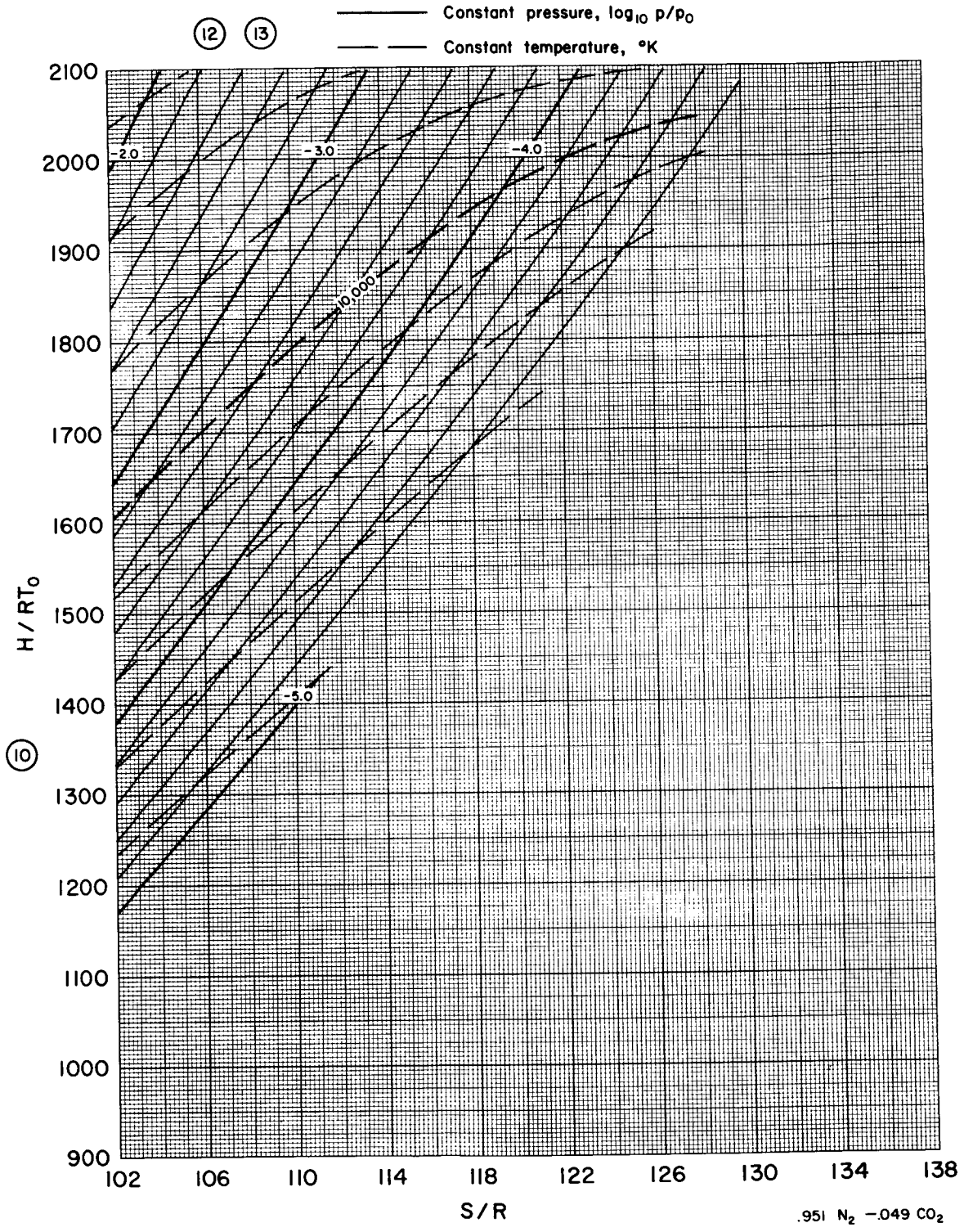
(j) Region 10.

Figure 2. - Continued.



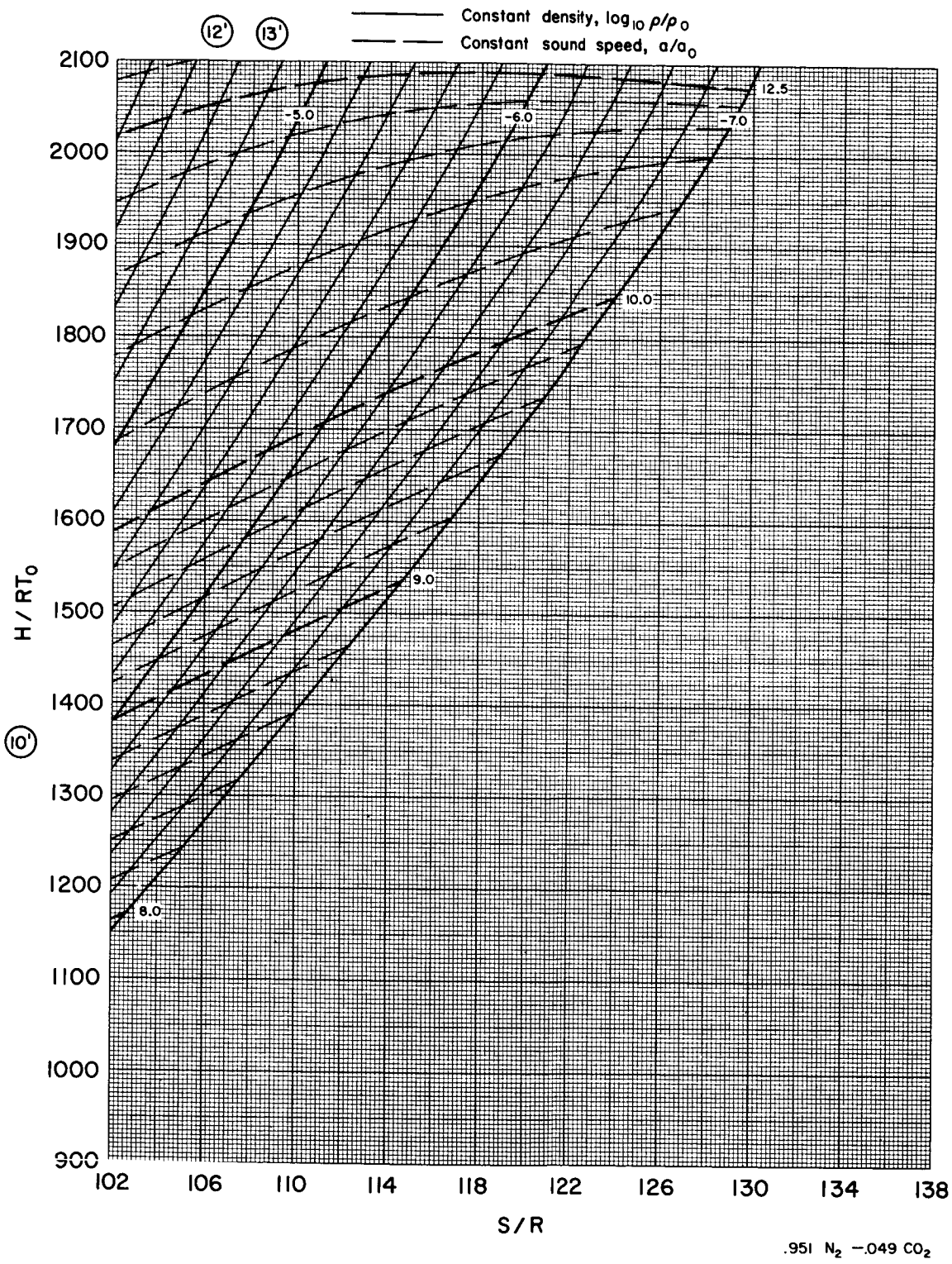
(j) Region 10 - Concluded.

Figure 2. - Continued.



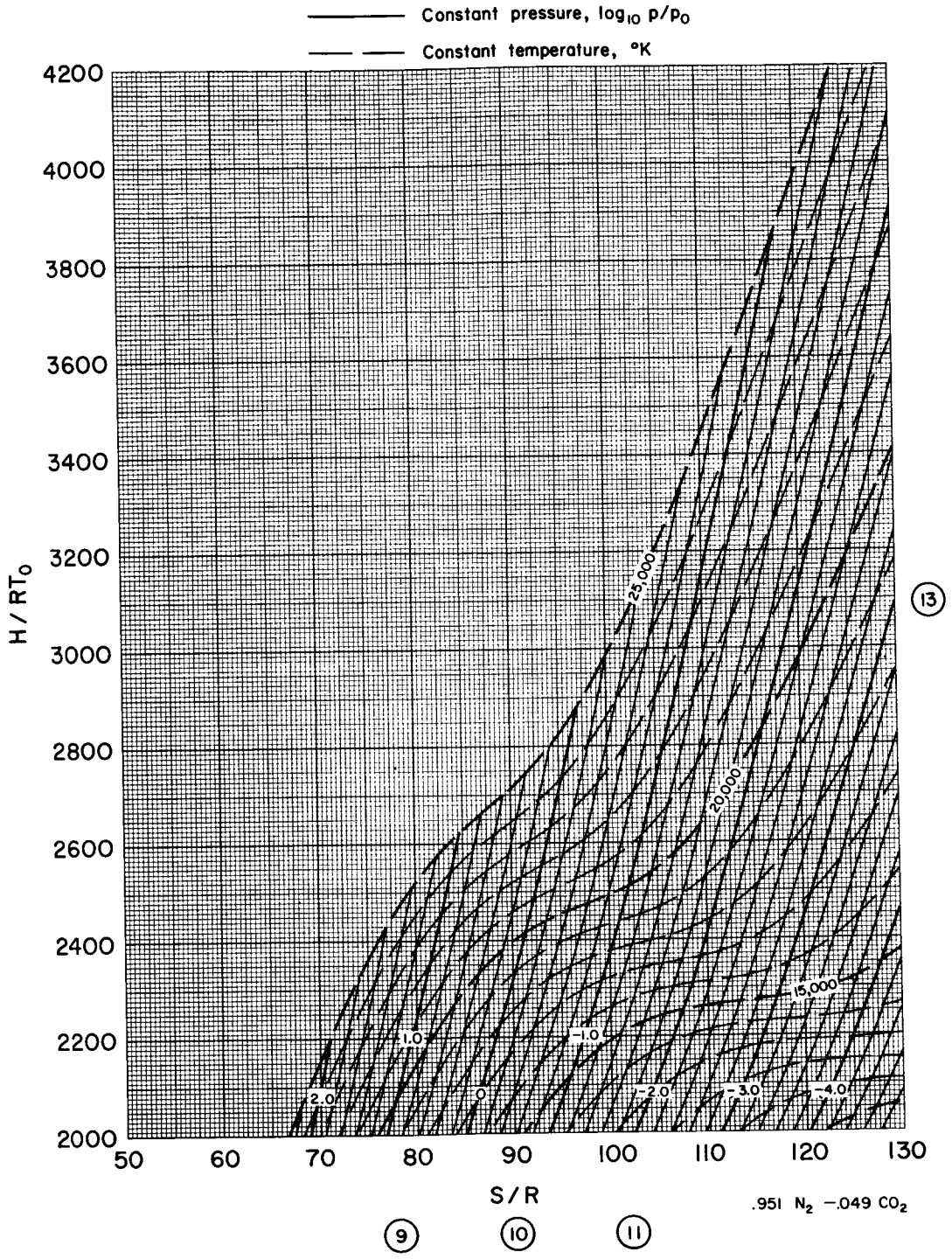
(k) Region 11.

Figure 2. - Continued.



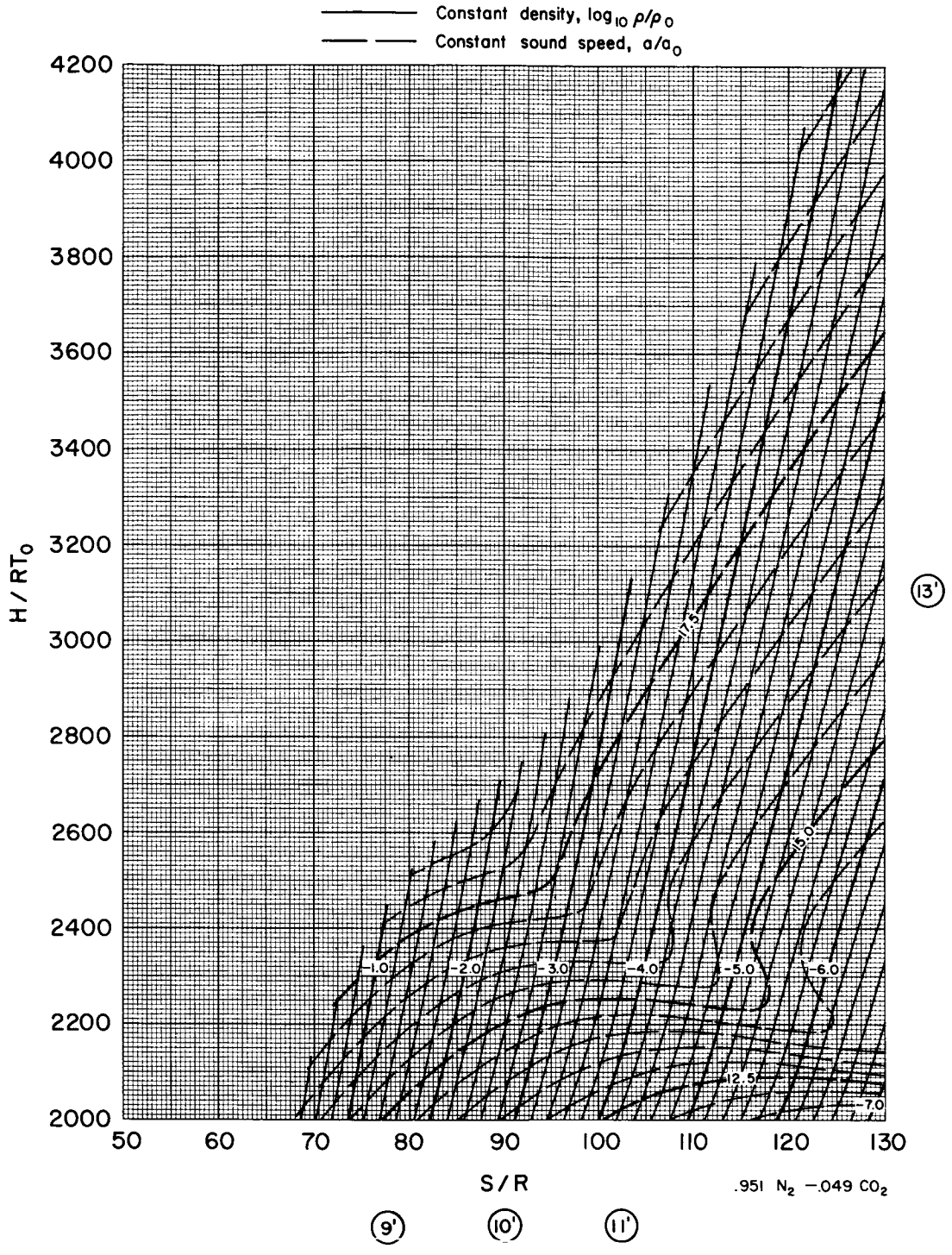
(k) Region 11 - Concluded.

Figure 2. - Continued.



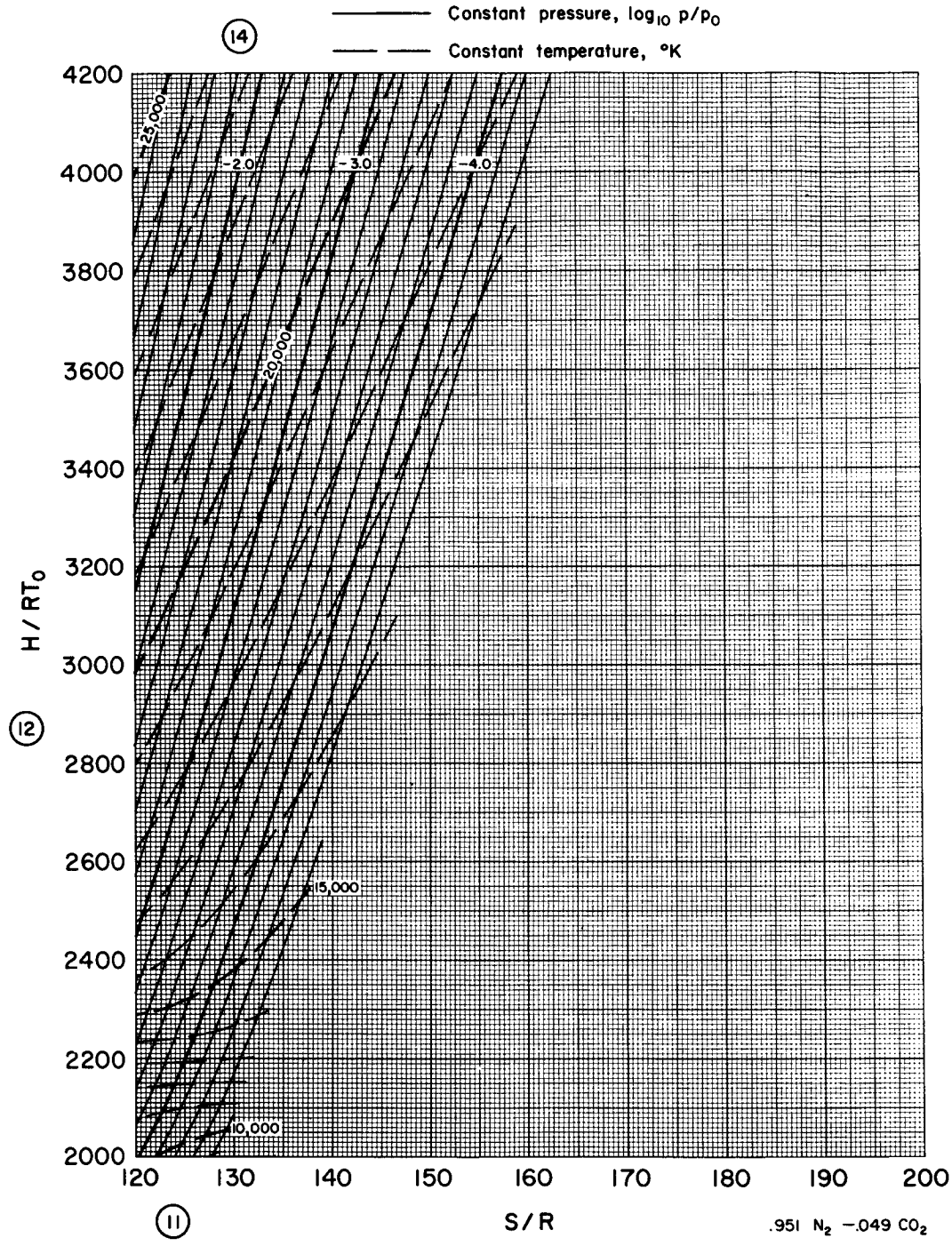
(l) Region 12.

Figure 2. - Continued.



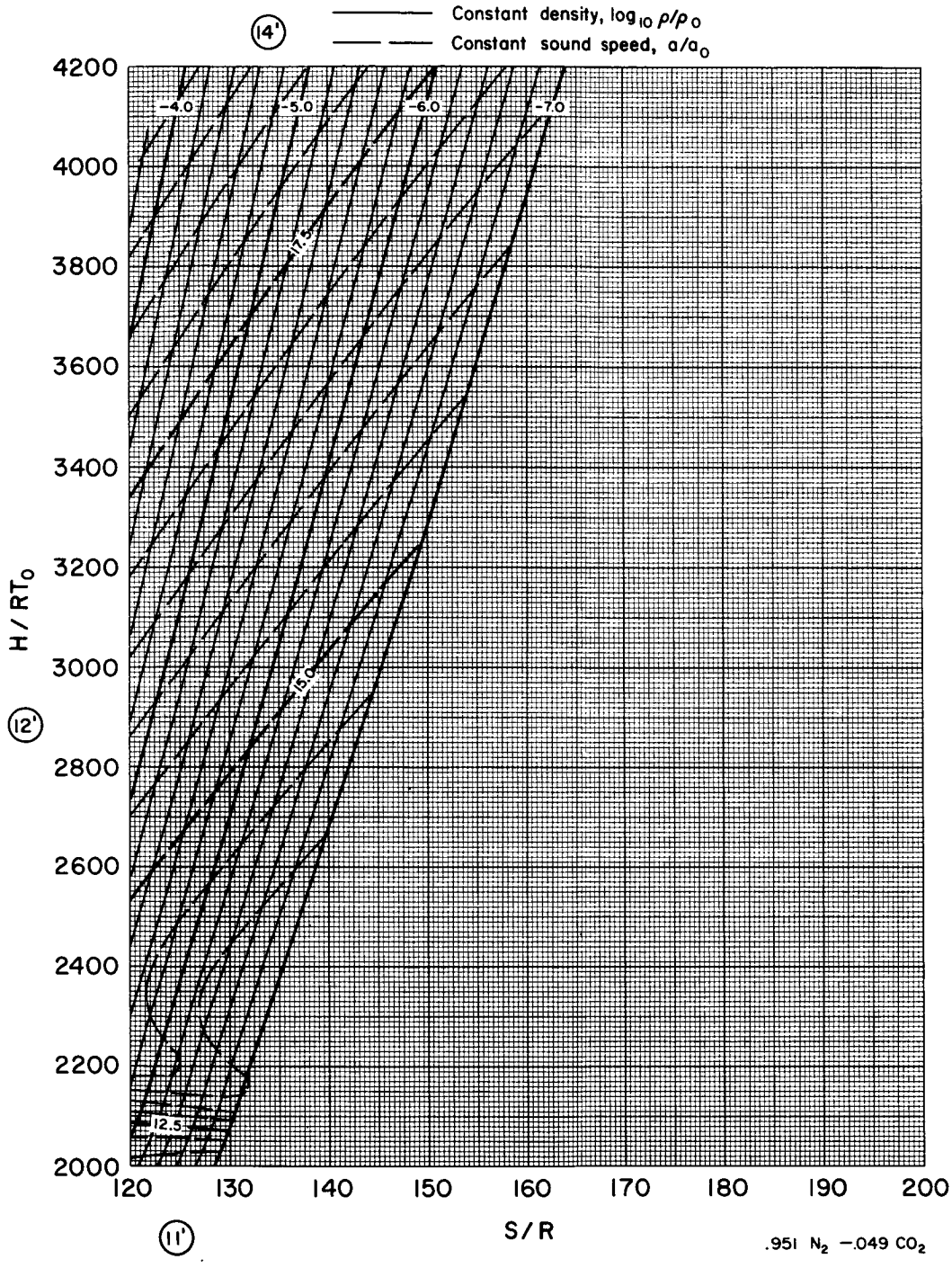
(*l*) Region 12 - Concluded.

Figure 2. - Continued.



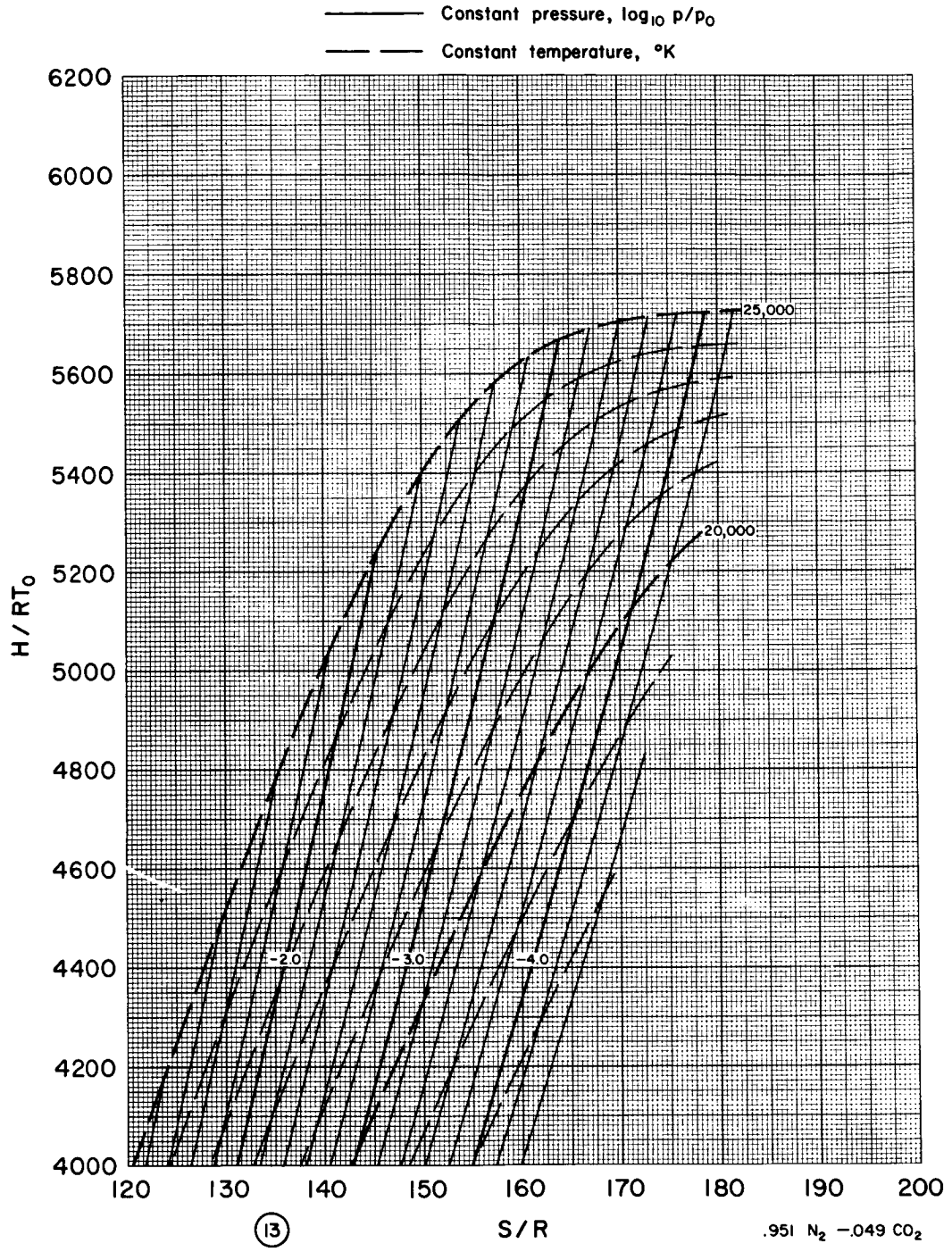
(m) Region 13.

Figure 2. - Continued.



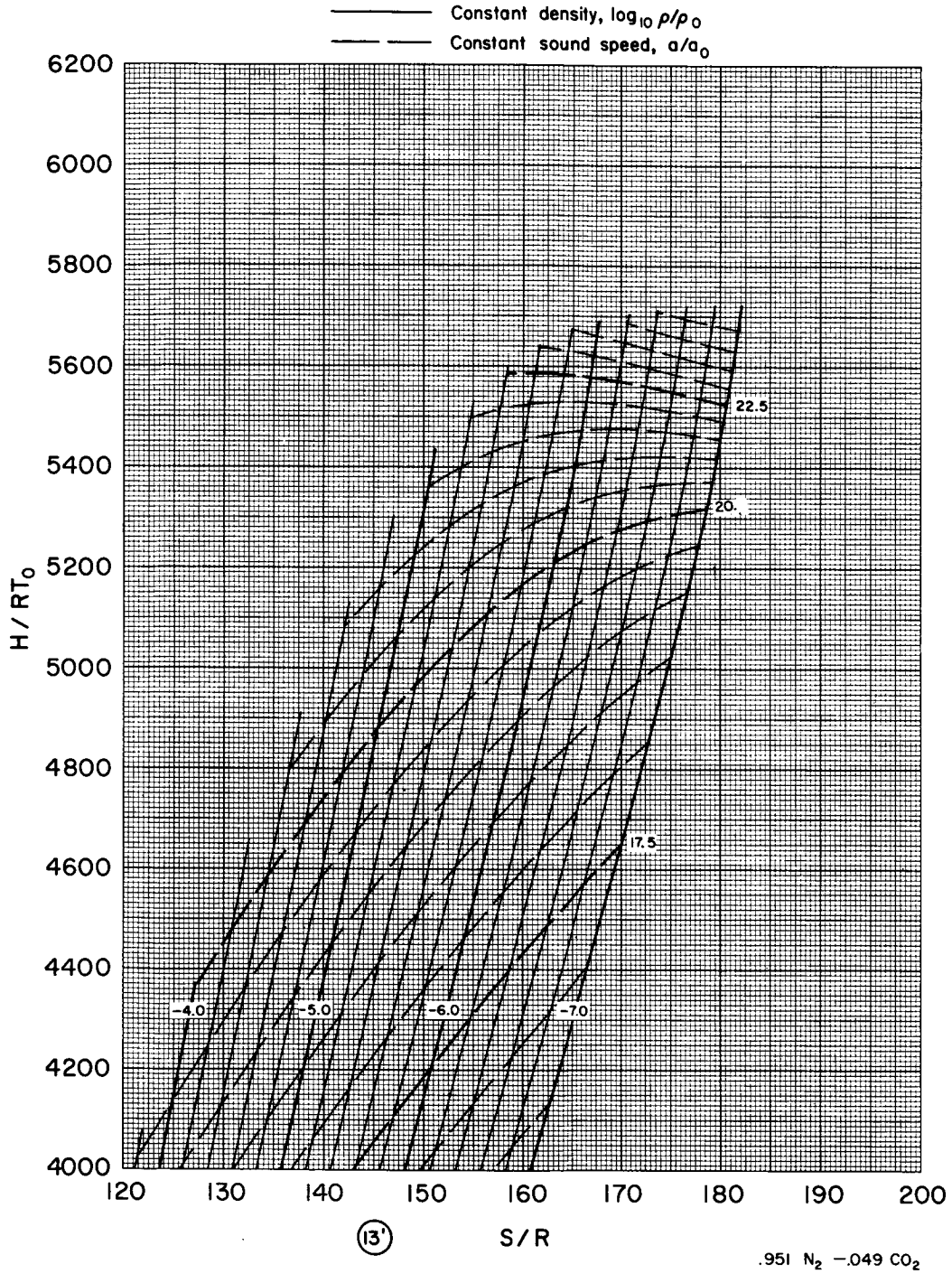
(m) Region 13 - Concluded.

Figure 2. - Continued.



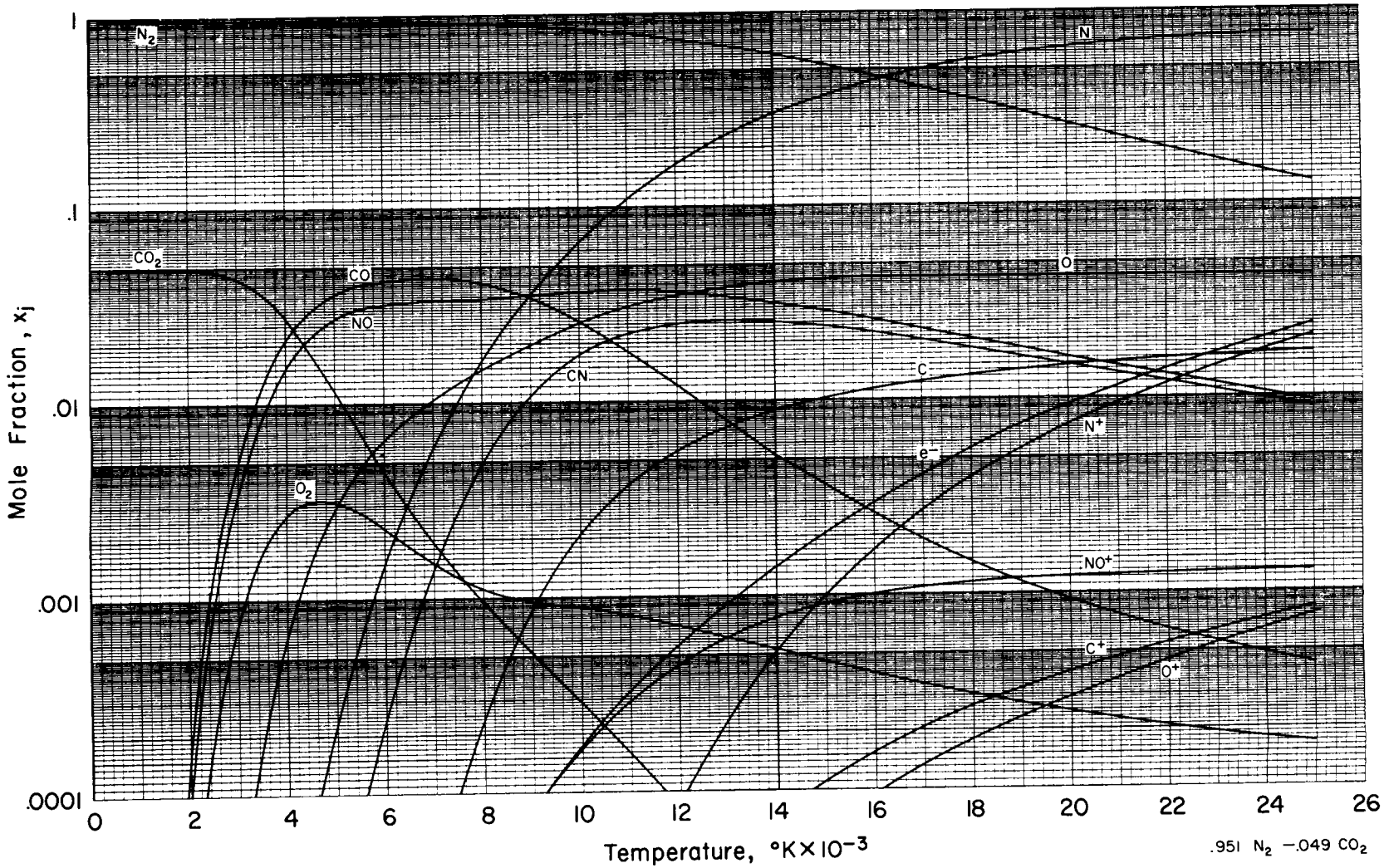
(n) Region 14.

Figure 2. - Continued.



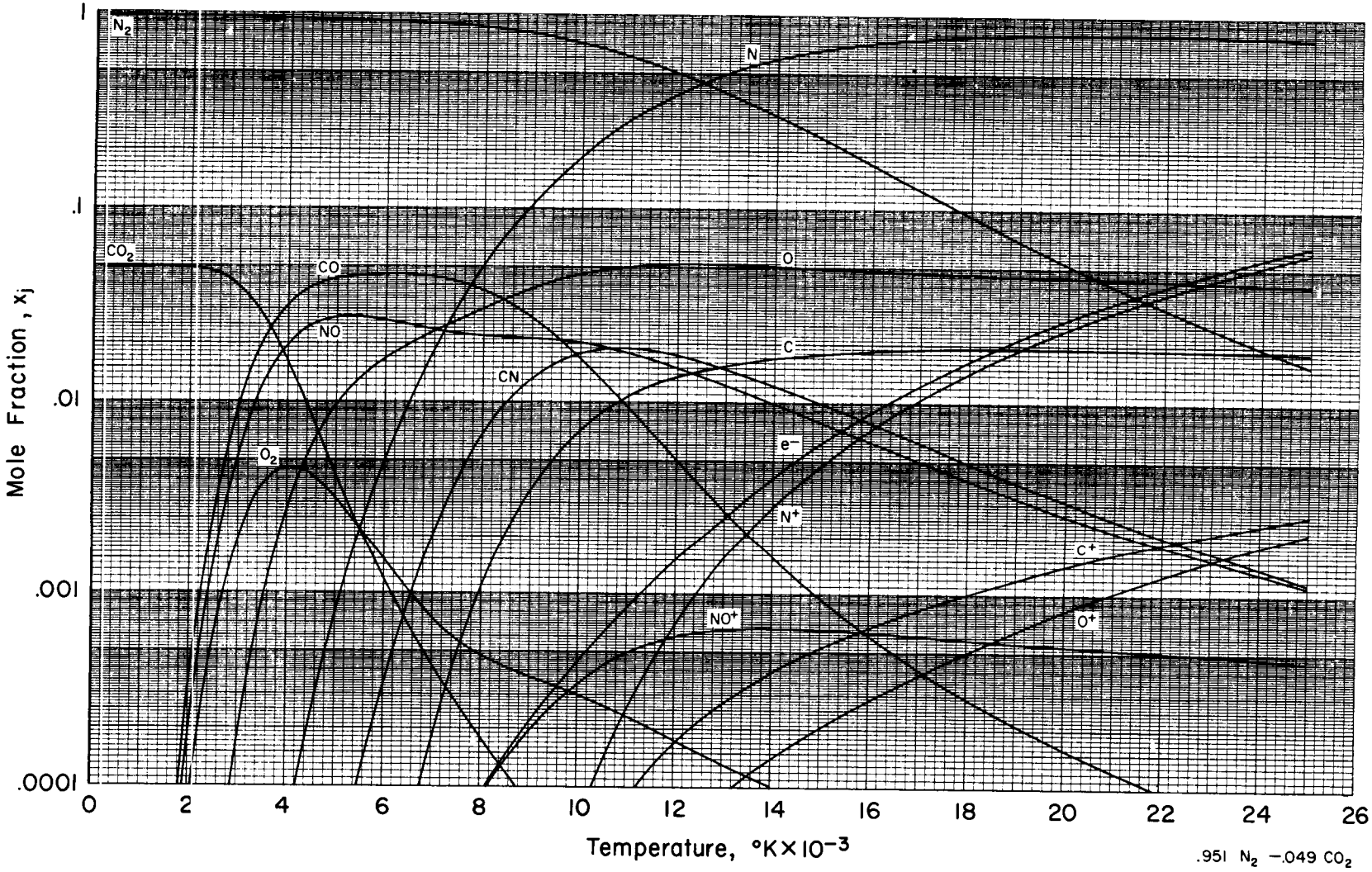
(n) Region 14 - Concluded.

Figure 2. - Concluded.



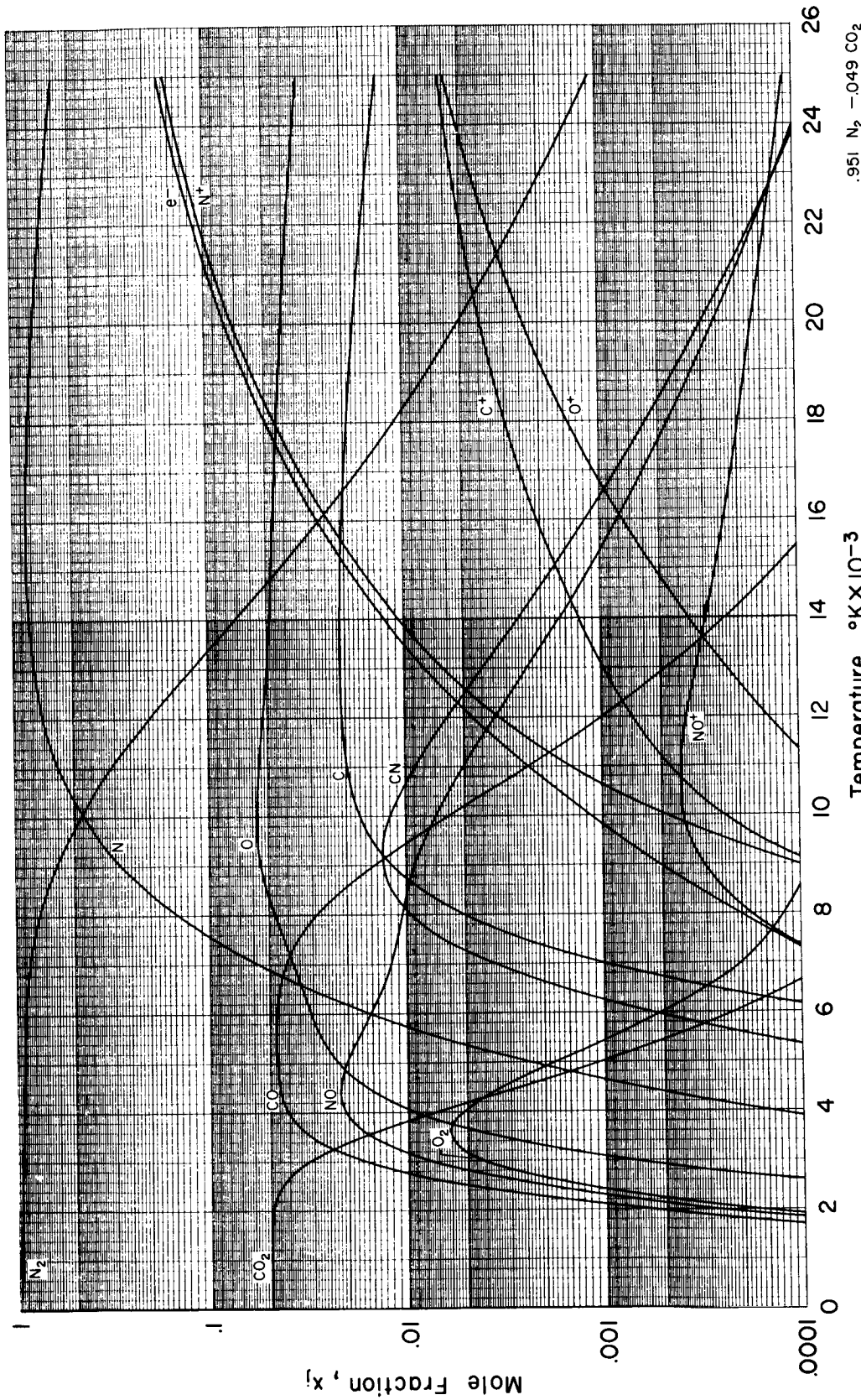
(a) $\rho/\rho_0 = 10^3$

Figure 3. - Equilibrium chemical composition.



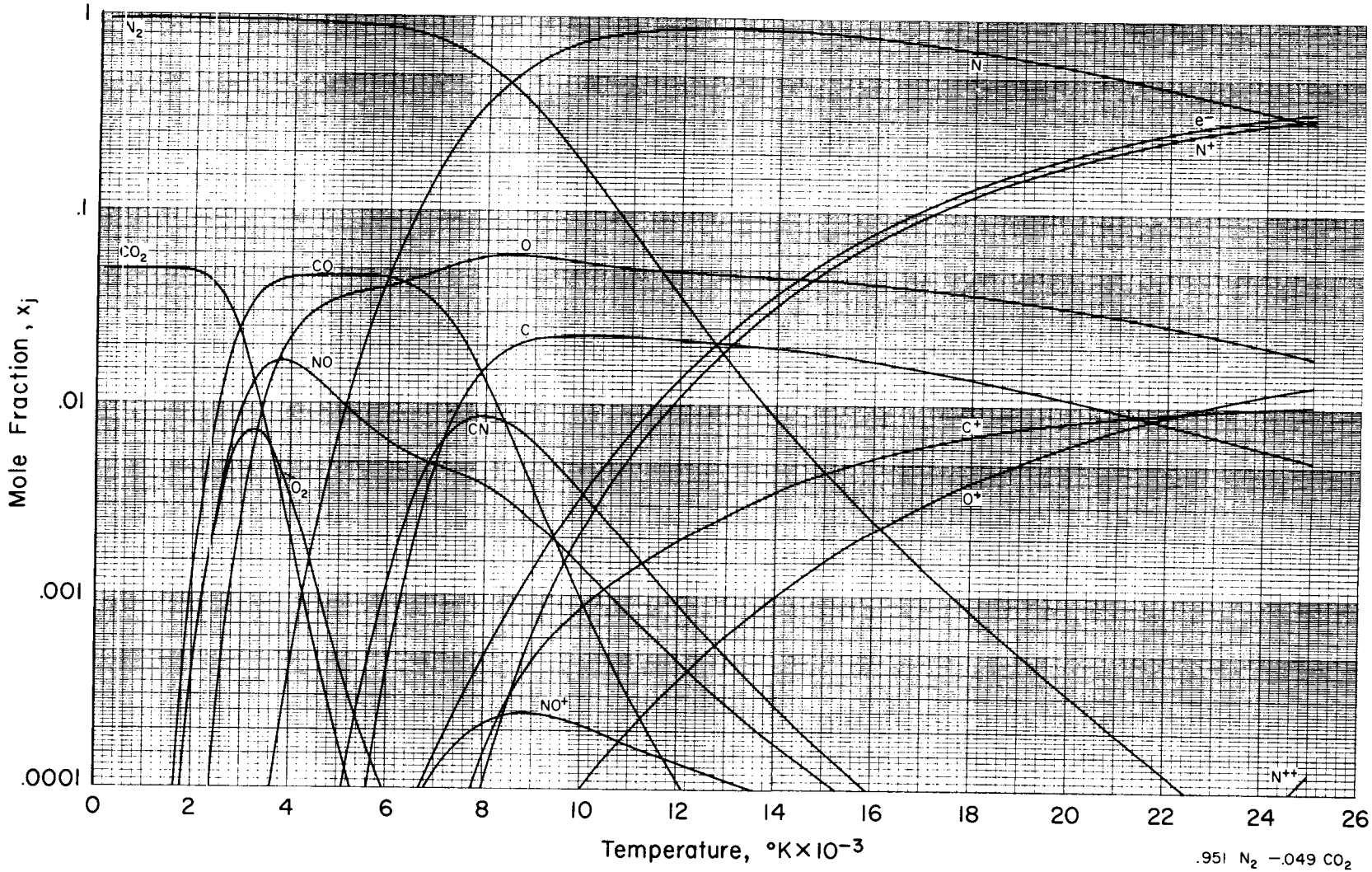
(b) $\rho/\rho_o = 10^2$

Figure 3. - Continued.



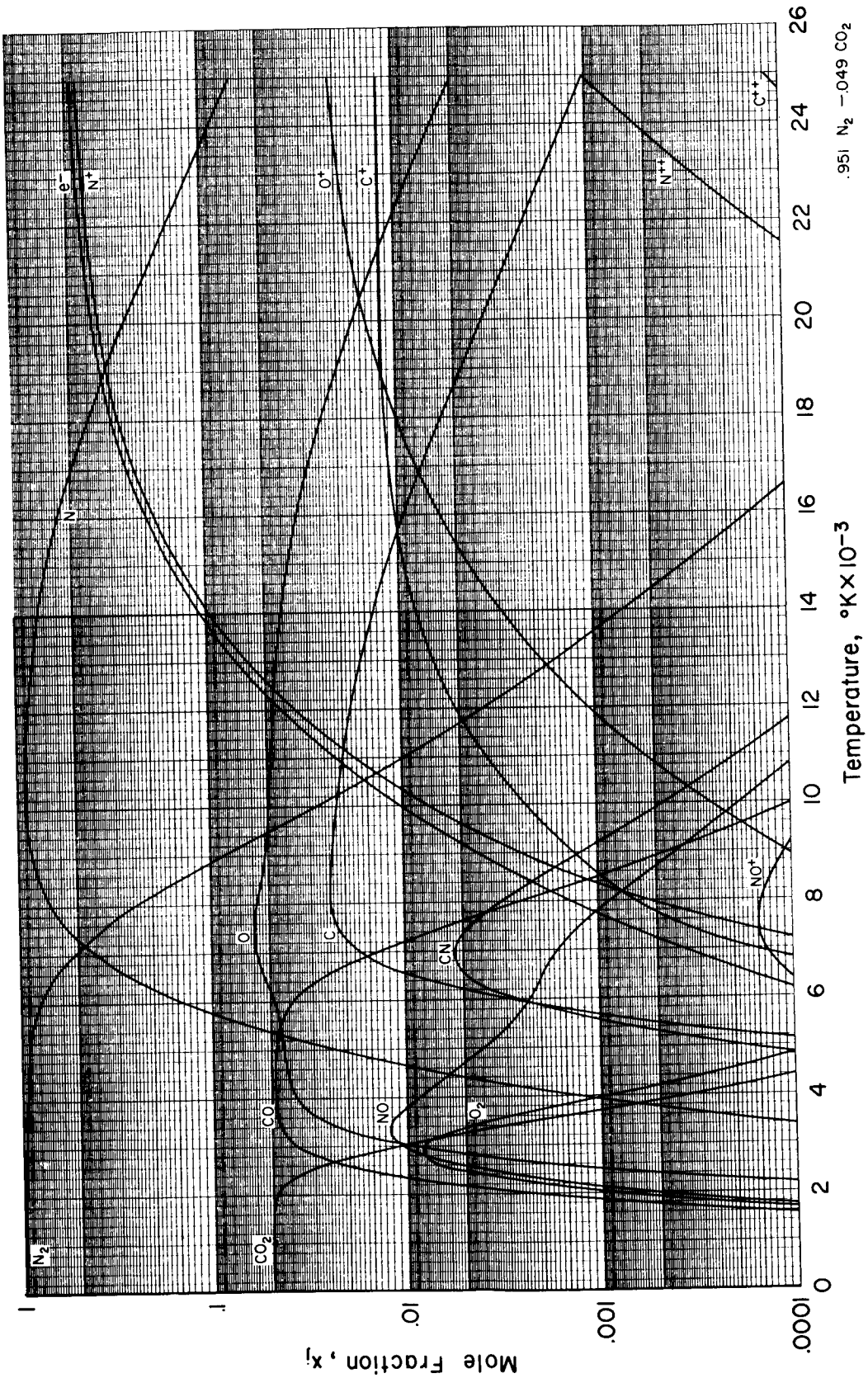
(c) $\rho/\rho_0 = 10$

Figure 3. - Continued.



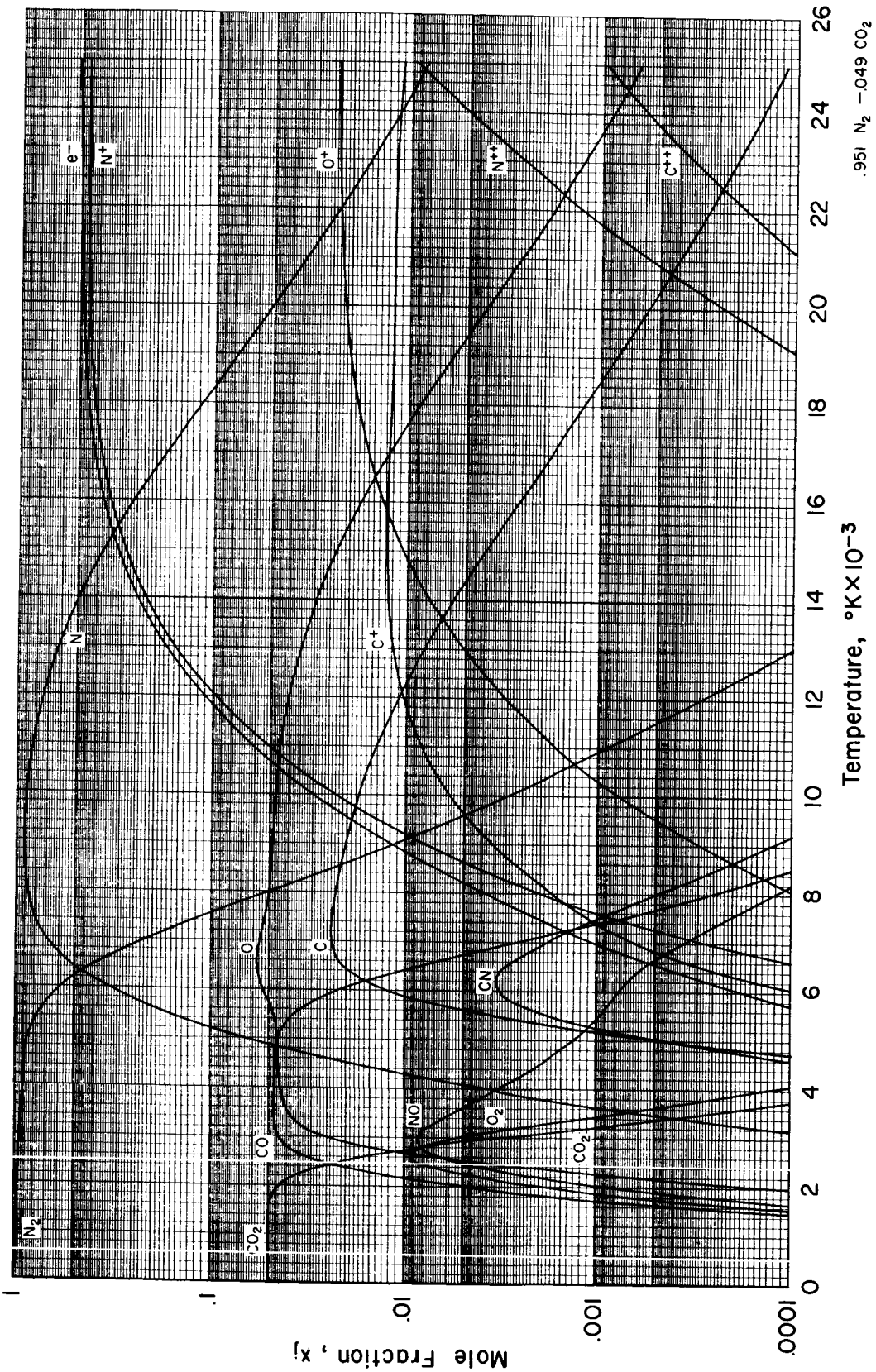
(d) $\rho/\rho_o = 1$

Figure 3. - Continued.



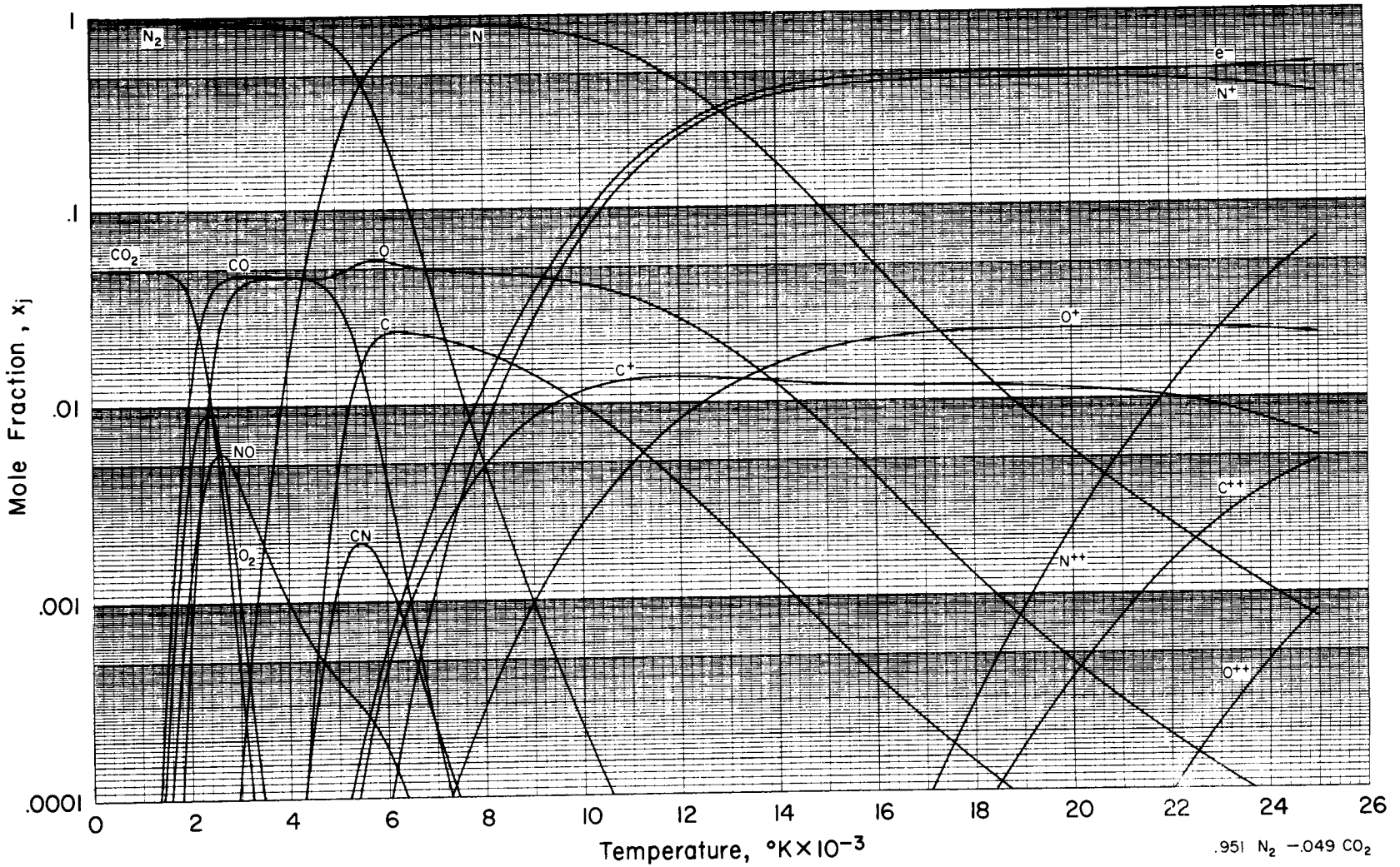
(e) $\rho/\rho_0 = 10^{-1}$

Figure 3. - Continued.



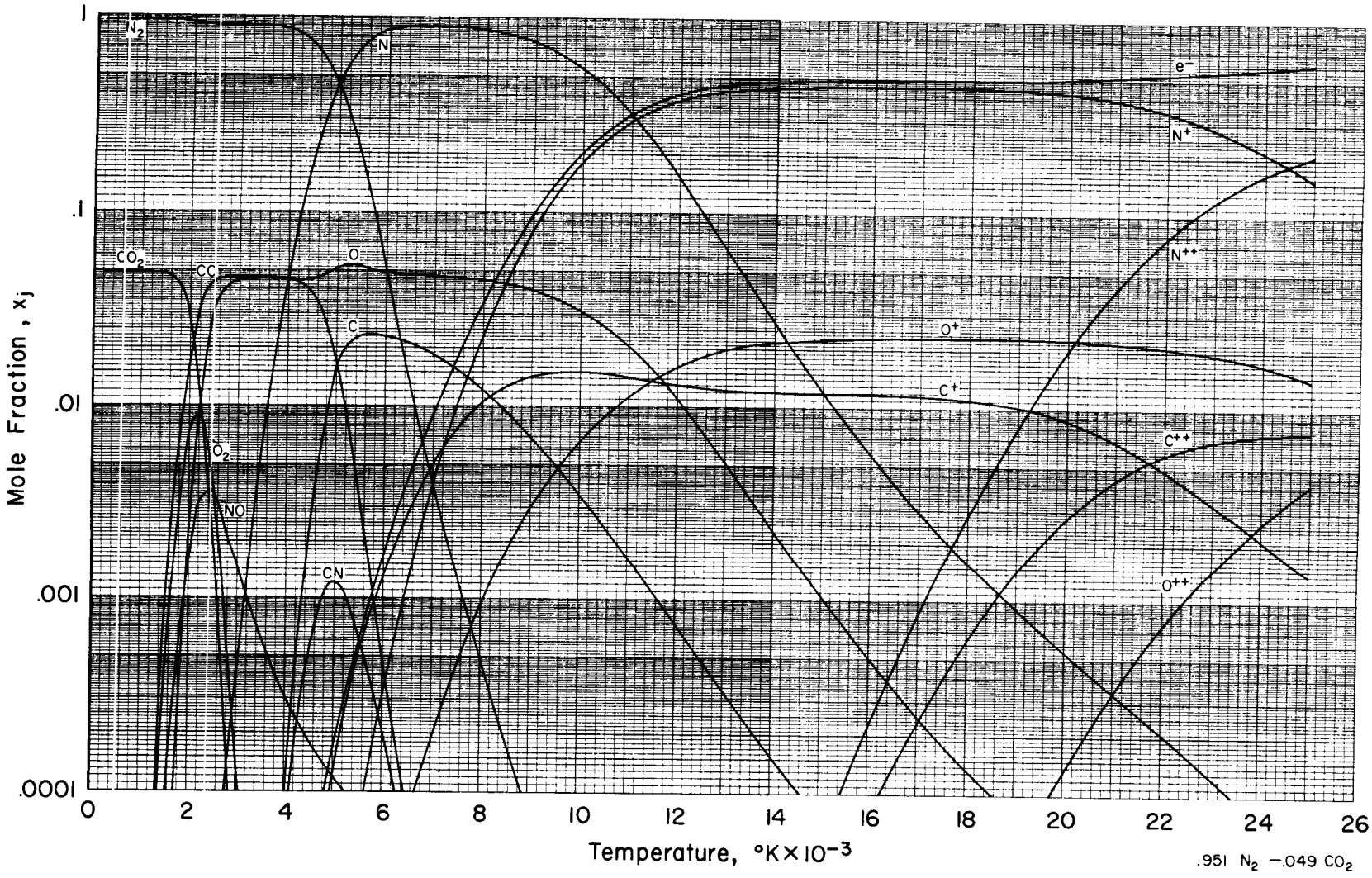
(f) $\rho/\rho_o = 10^{-2}$

Figure 3. - Continued.



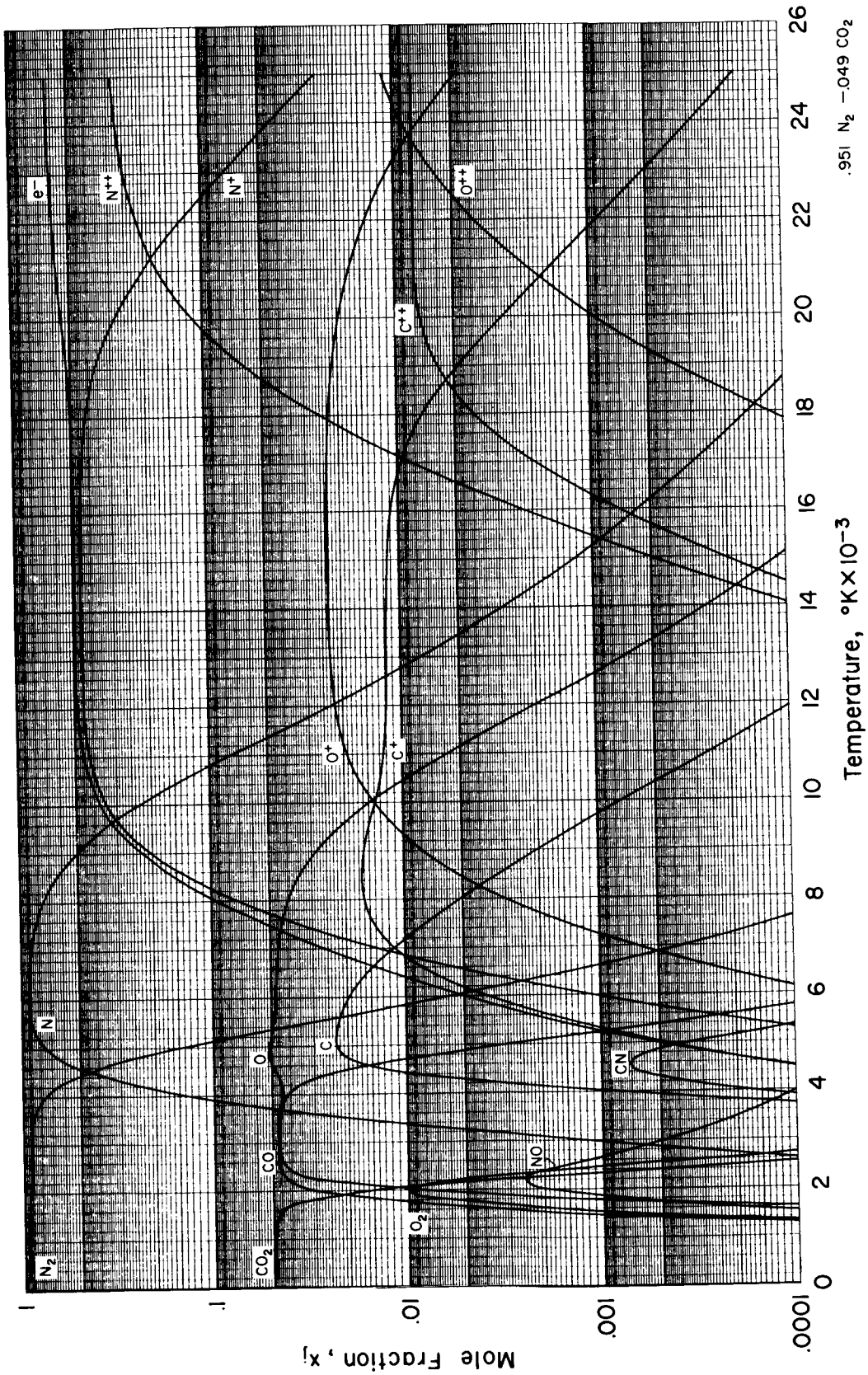
(g) $\rho/\rho_o = 10^{-3}$

Figure 3. - Continued.



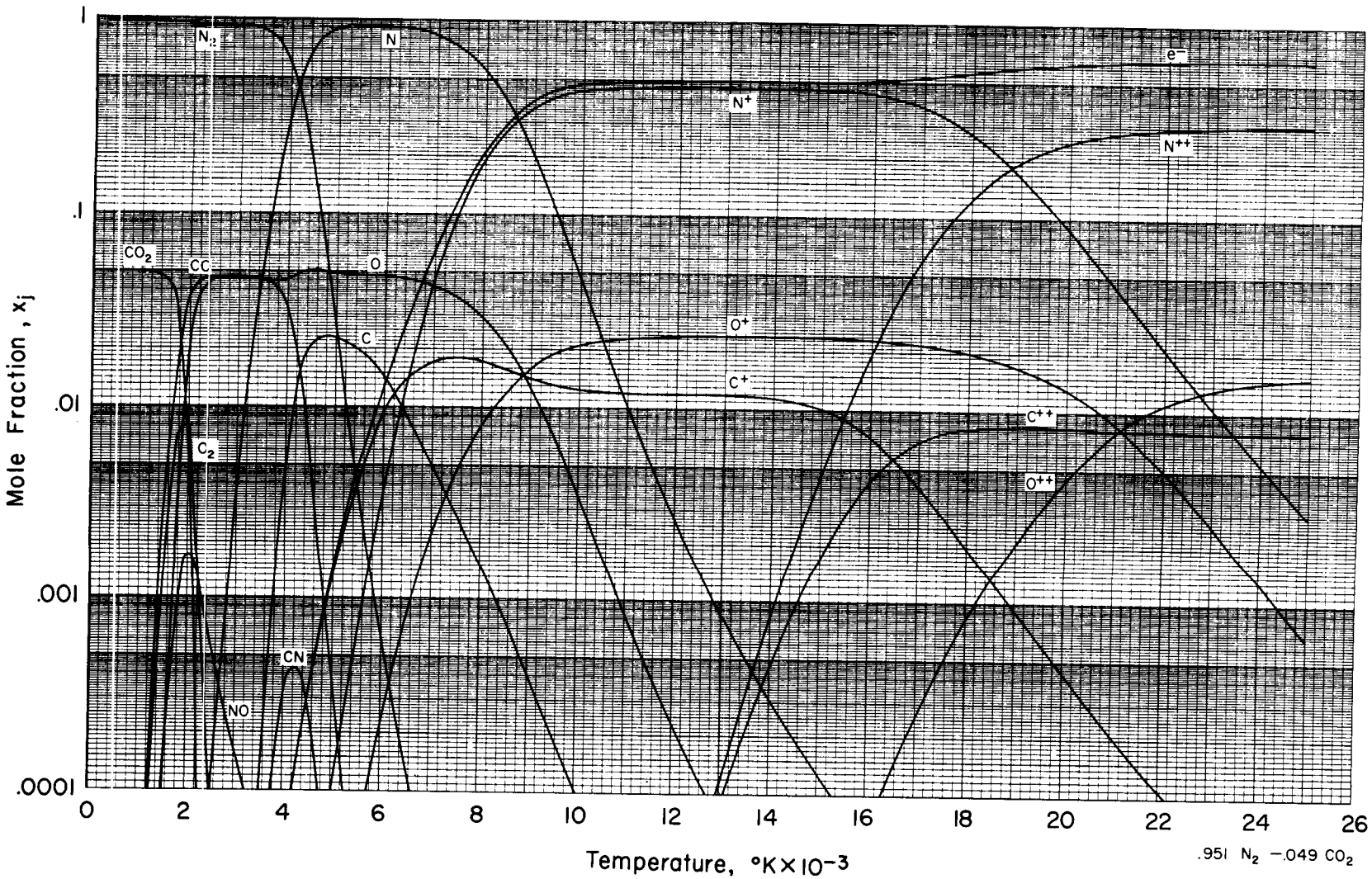
(h) $\rho/\rho_o = 10^{-4}$

Figure 3. - Continued.



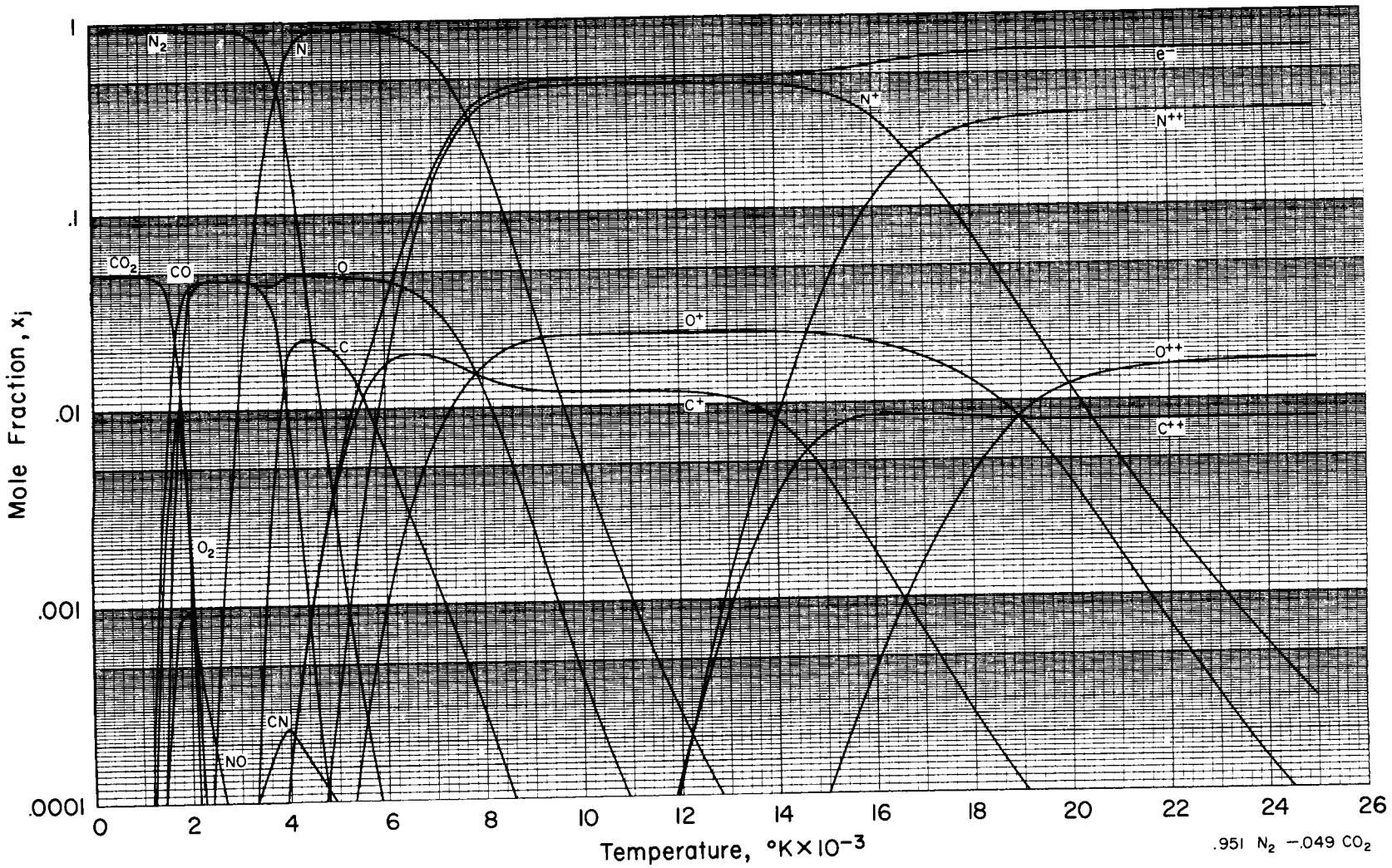
(i) $\rho/\rho_0 = 10^{-5}$

Figure 3. - Continued.



(j) $\rho/\rho_o = 10^{-6}$

Figure 3. - Continued.



(k) $\rho/\rho_o = 10^{-7}$

Figure 3. - Concluded.

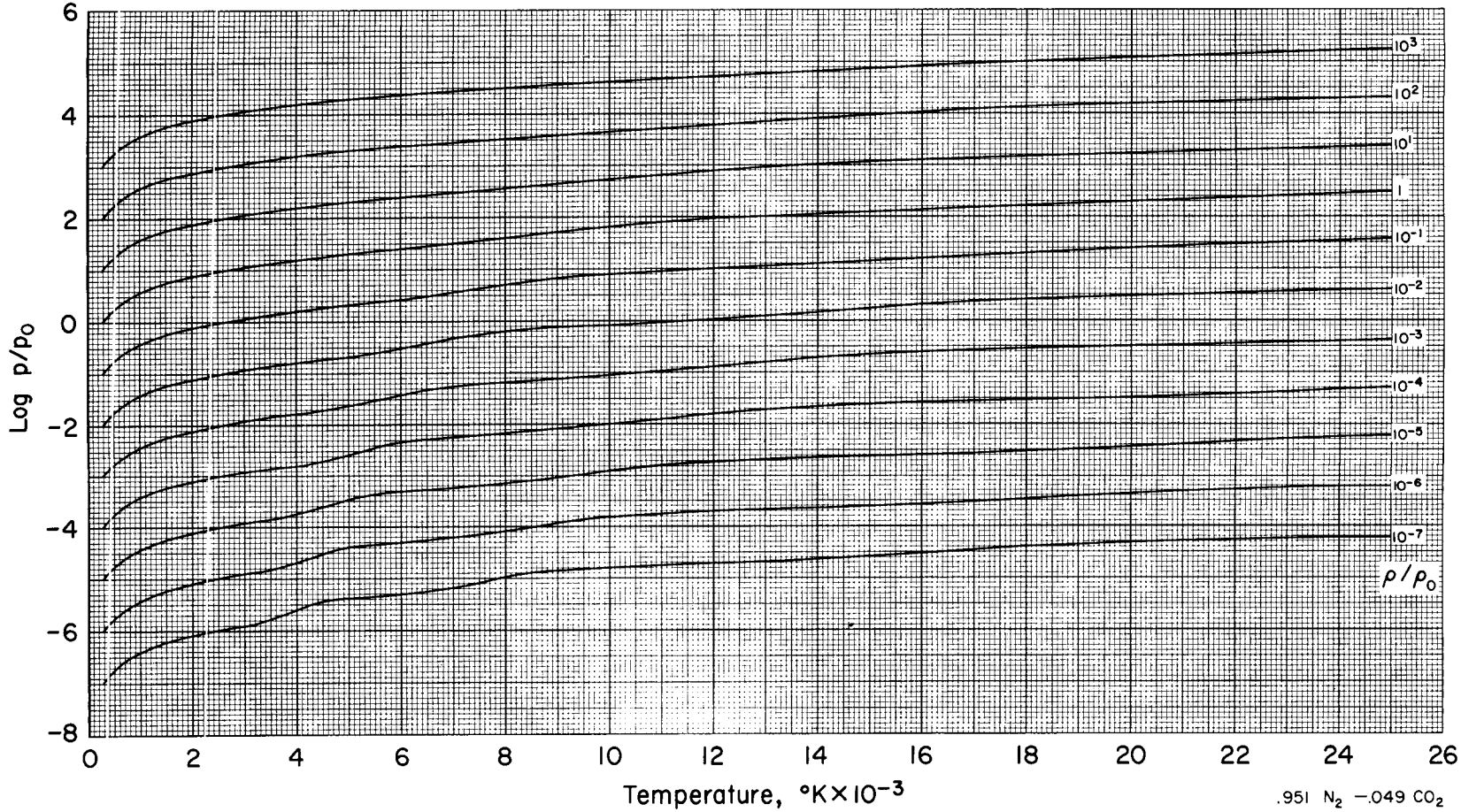


Figure 4. - Pressure as a function of temperature.

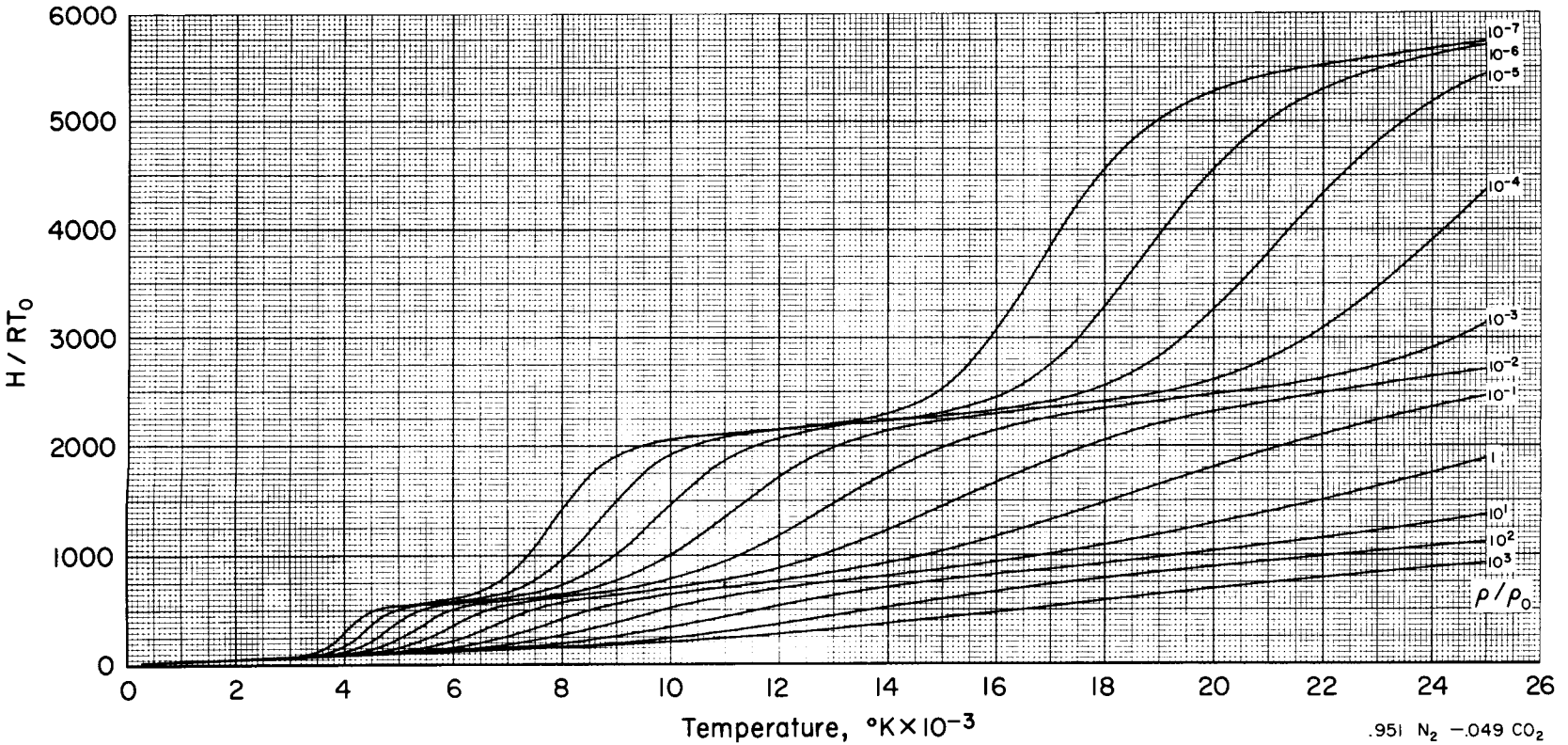


Figure 5. - Enthalpy as a function of temperature.

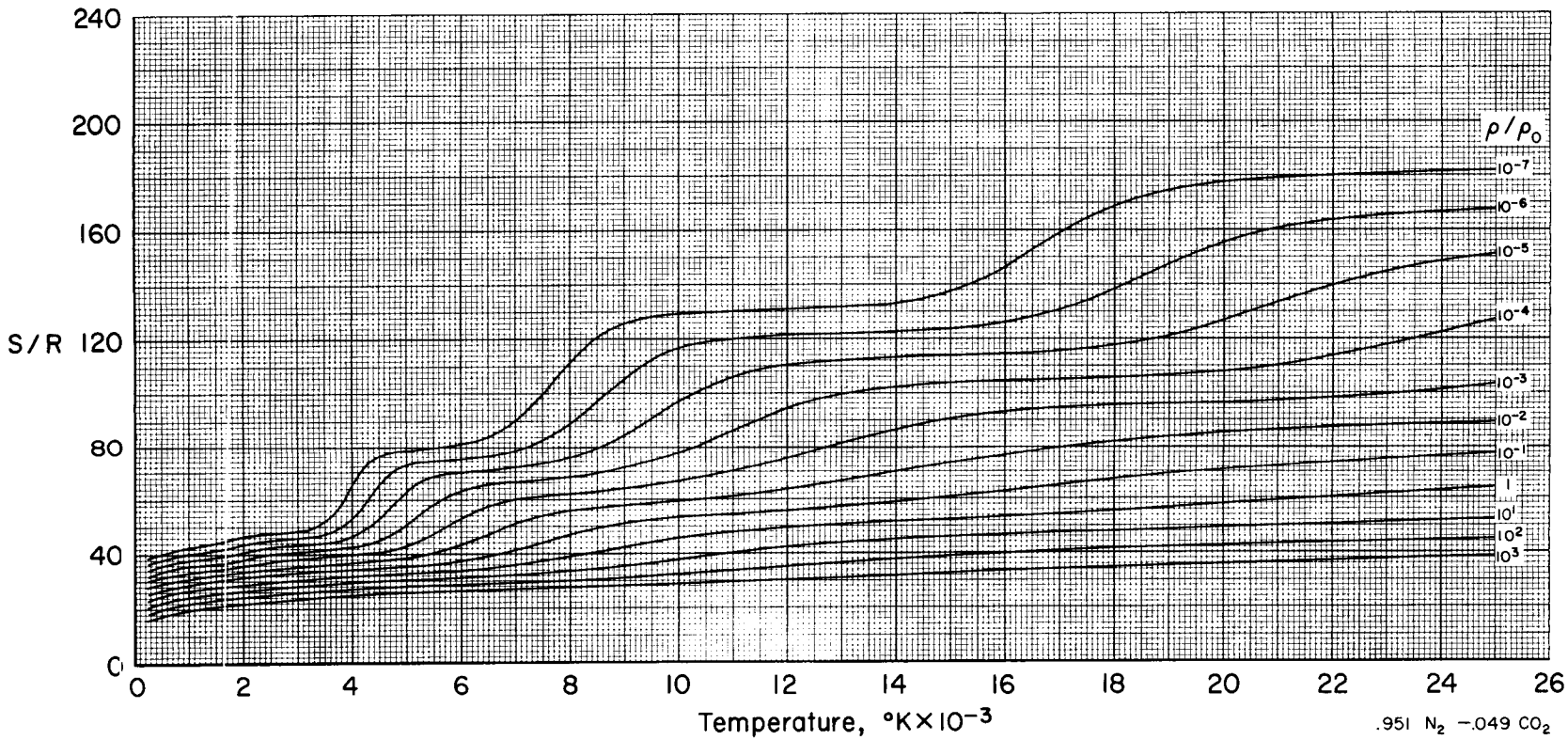


Figure 6. - Entropy as a function of temperature.

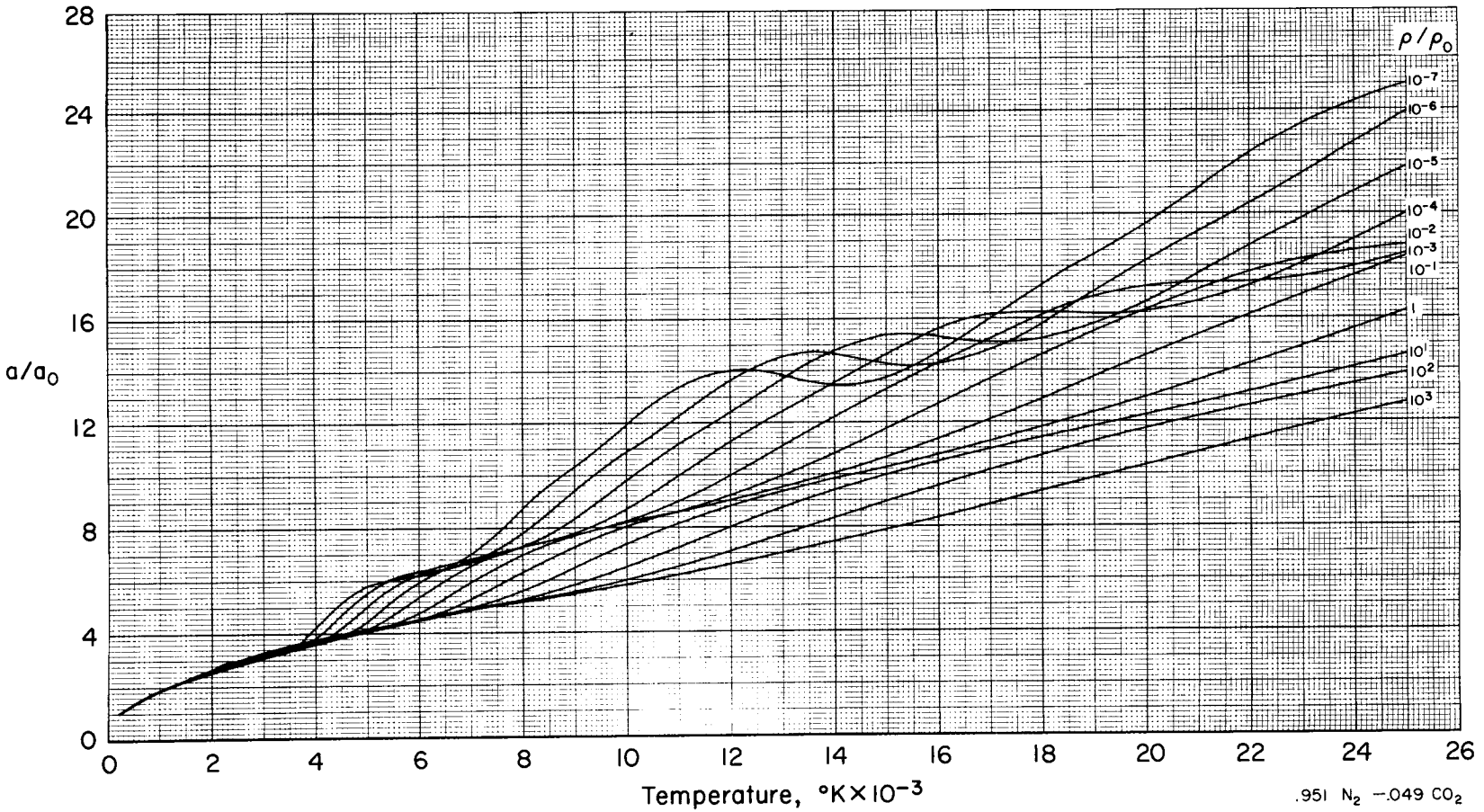


Figure 7. - Sound speed as a function of temperature.

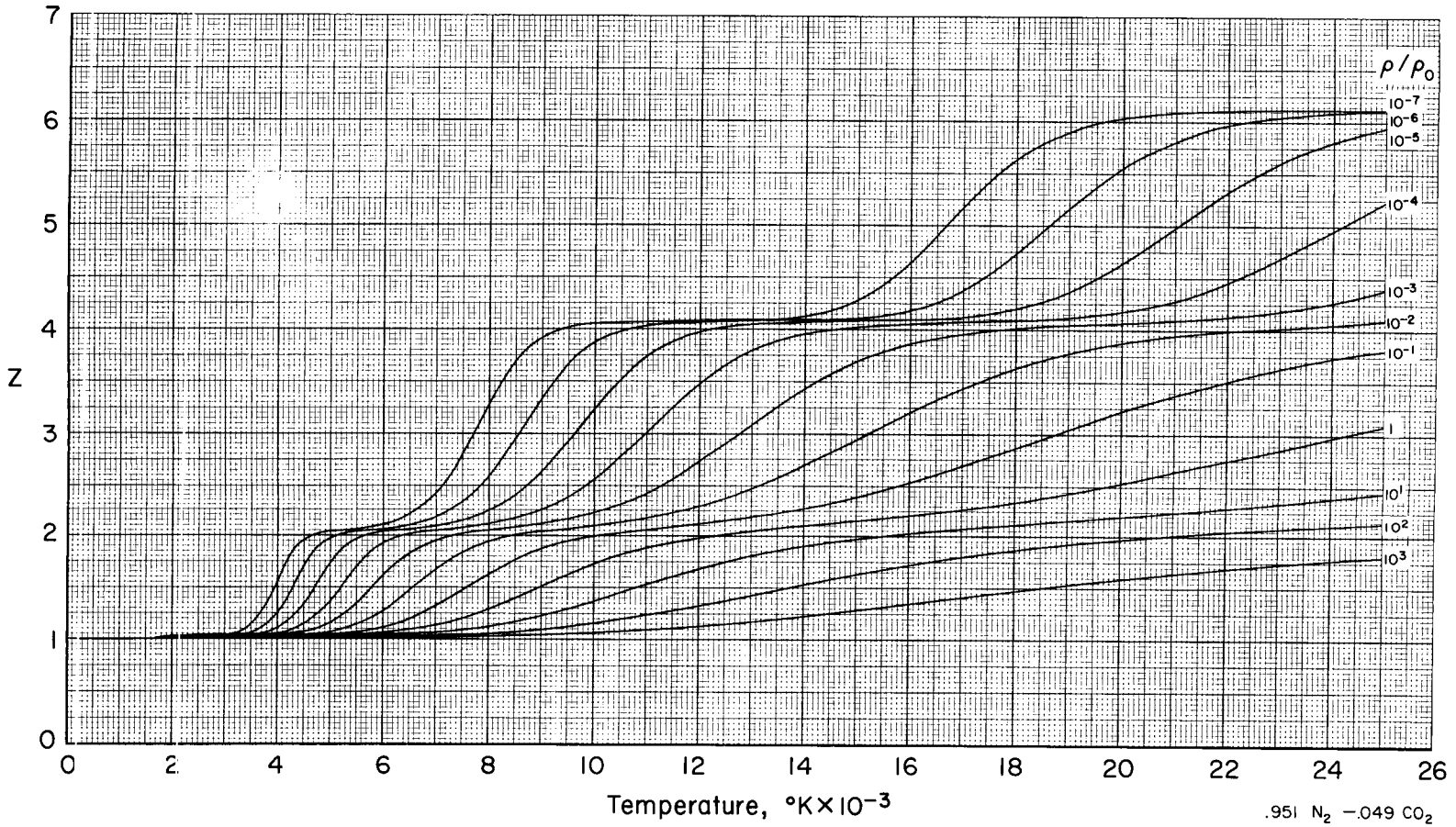
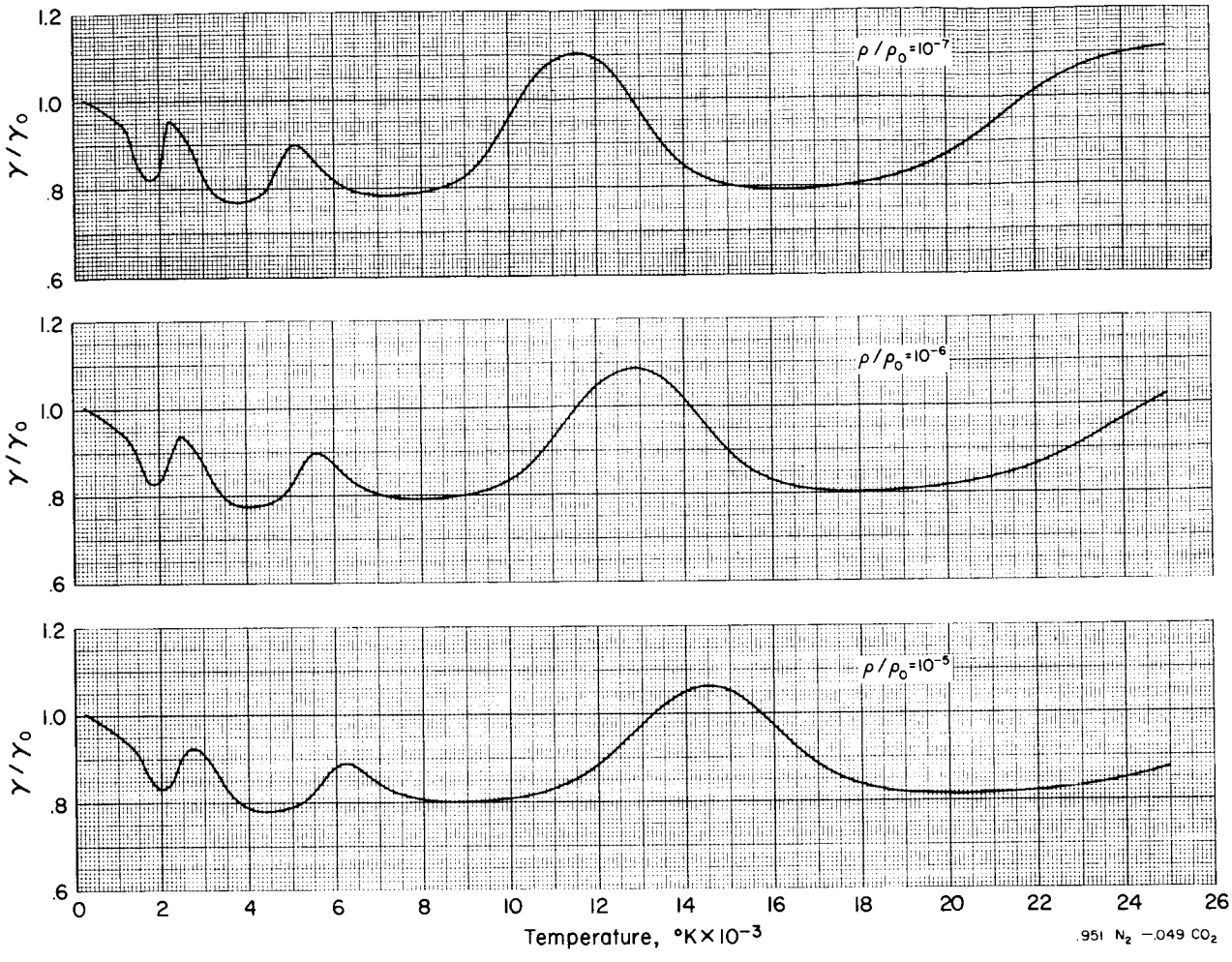
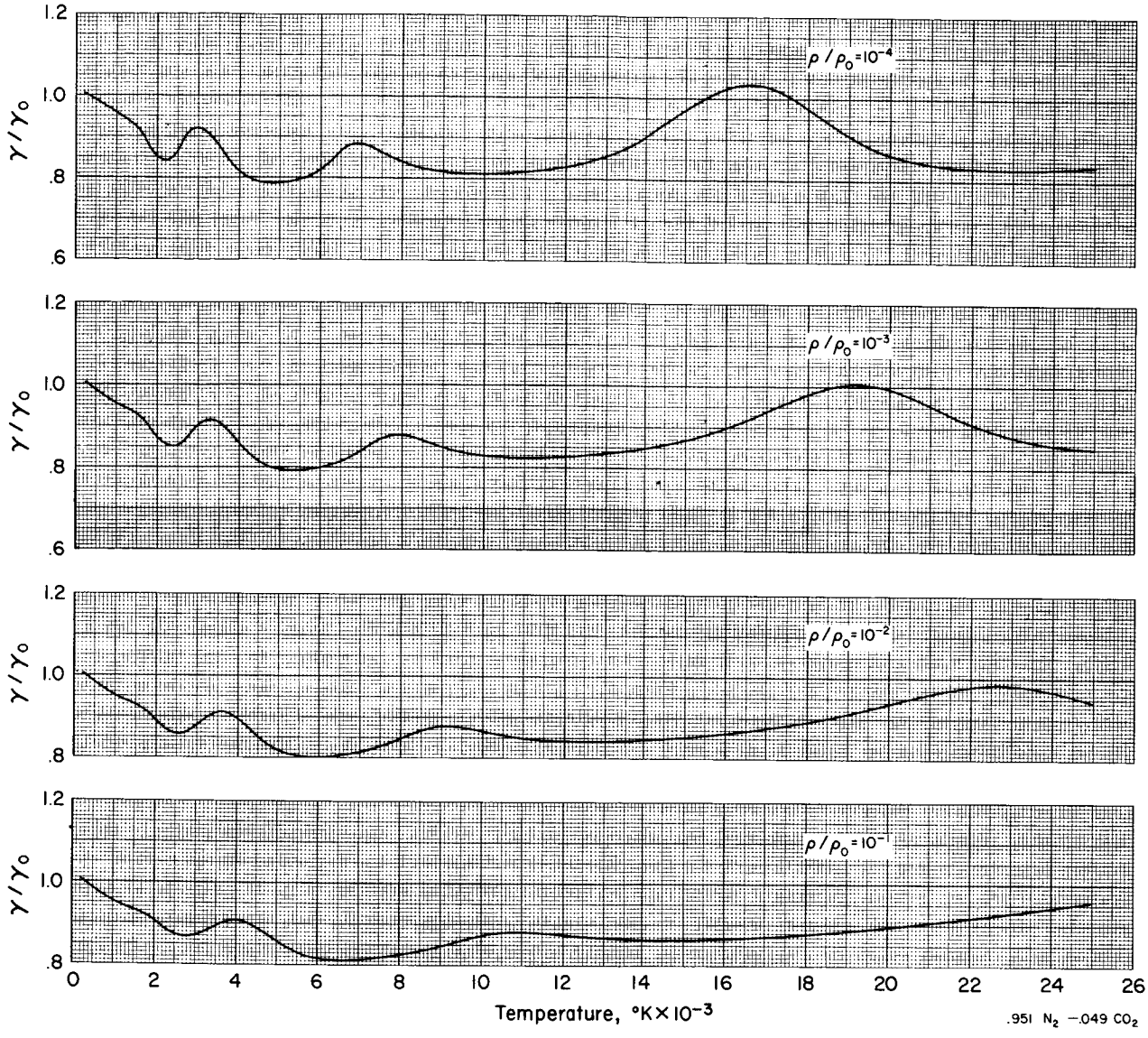


Figure 8. - Compressibility as a function of temperature.



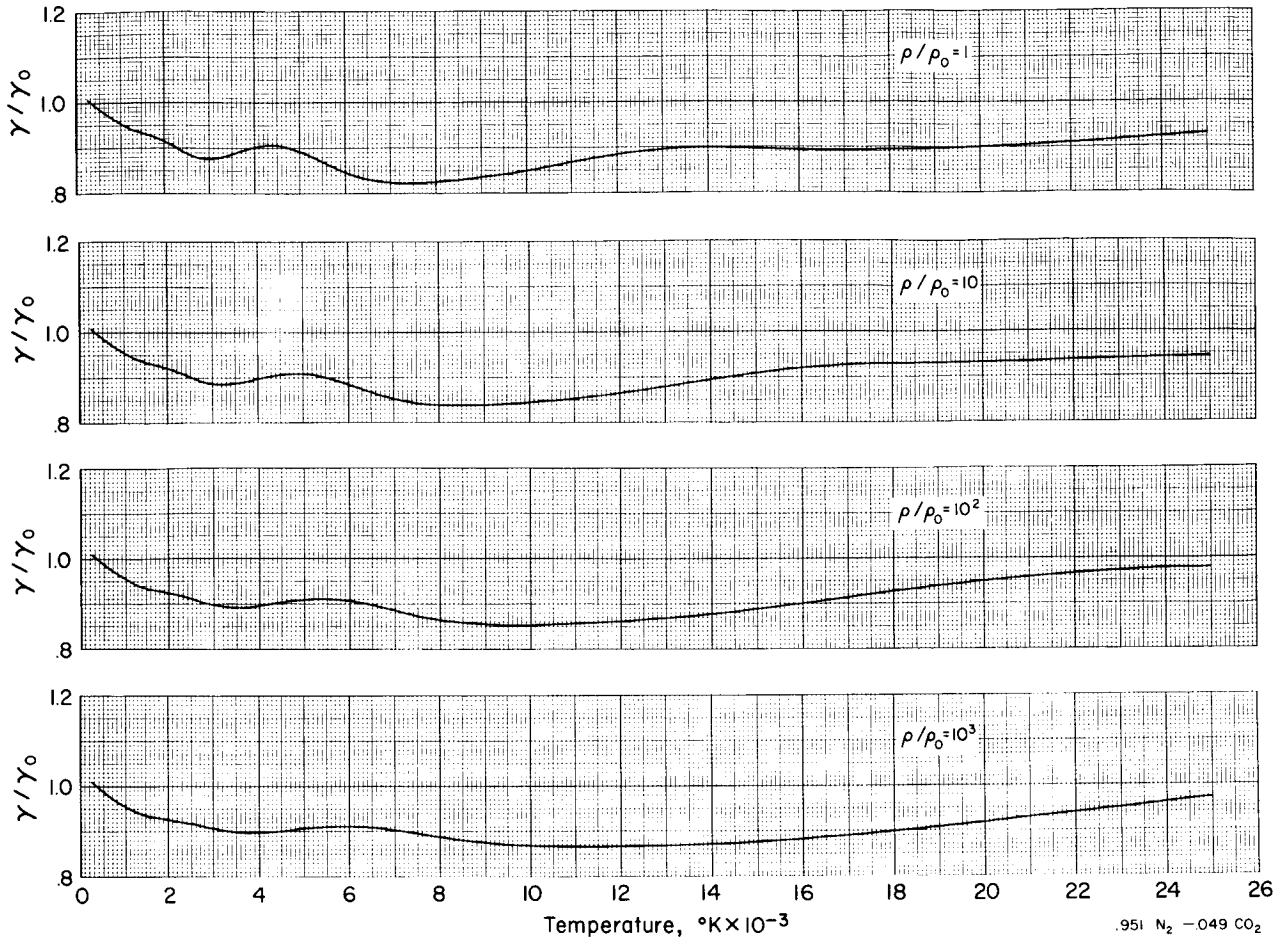
(a) $\rho/\rho_o = 10^{-7}$ to 10^{-5}; $\gamma_o = 1.393$

Figure 9. - Isentropic exponent as a function of temperature.



(b) $\rho/\rho_o = 10^{-4}$ to 10^{-1}; $\gamma_o = 1.393$

Figure 9. - Continued.



(c) $\rho/\rho_o = 1$ to 10^3; $\gamma_o = 1.393$

Figure 9. - Concluded.

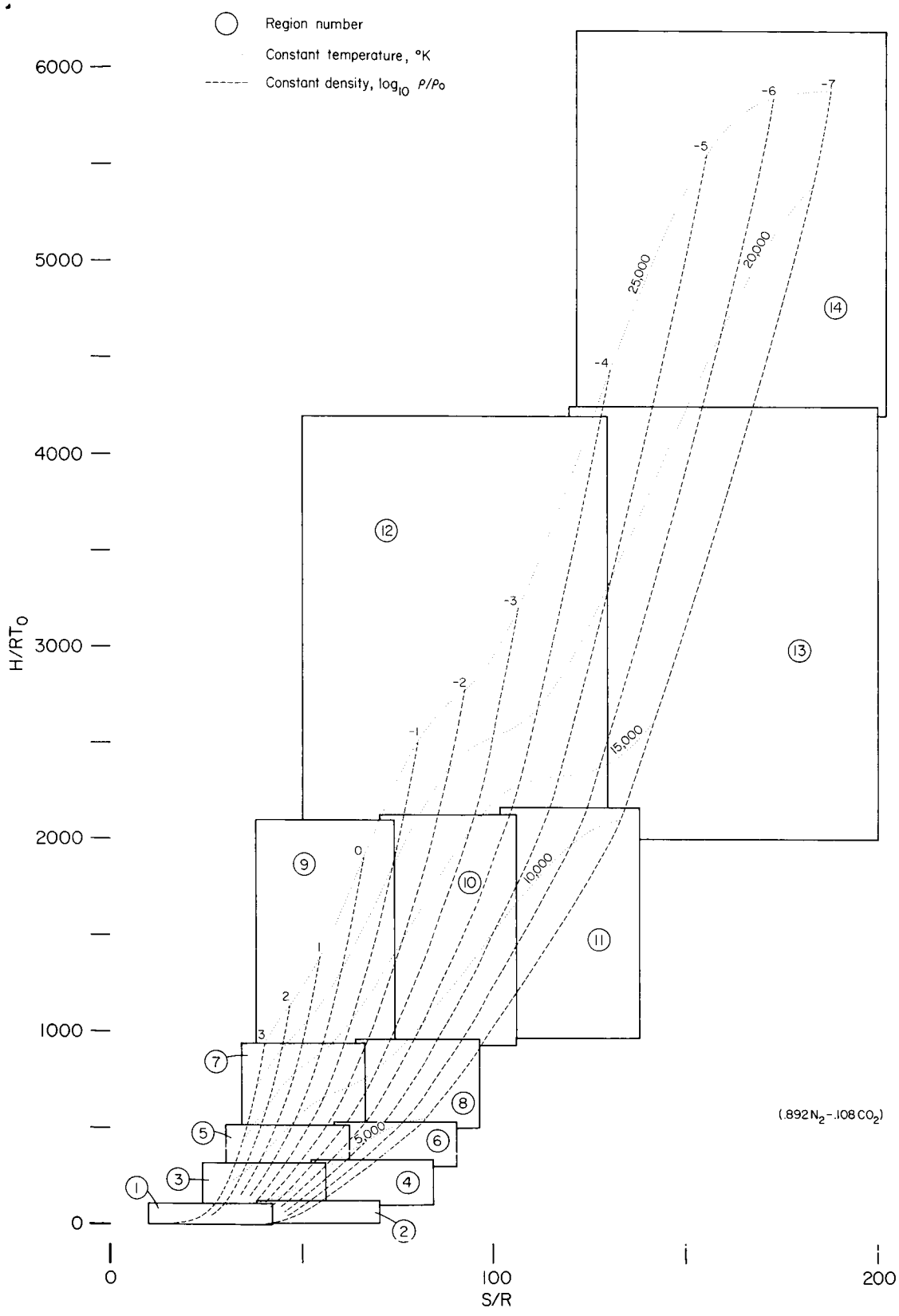
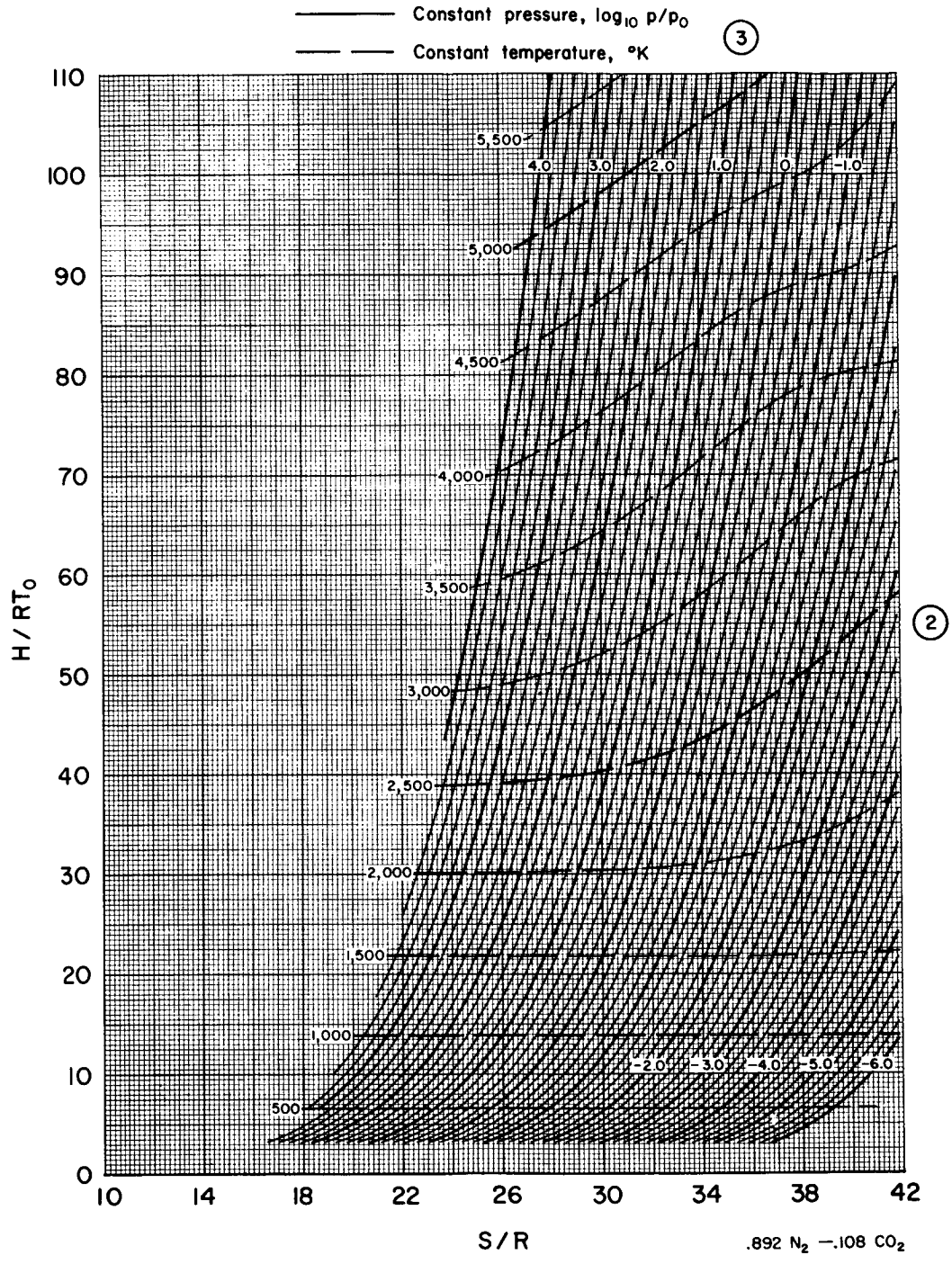
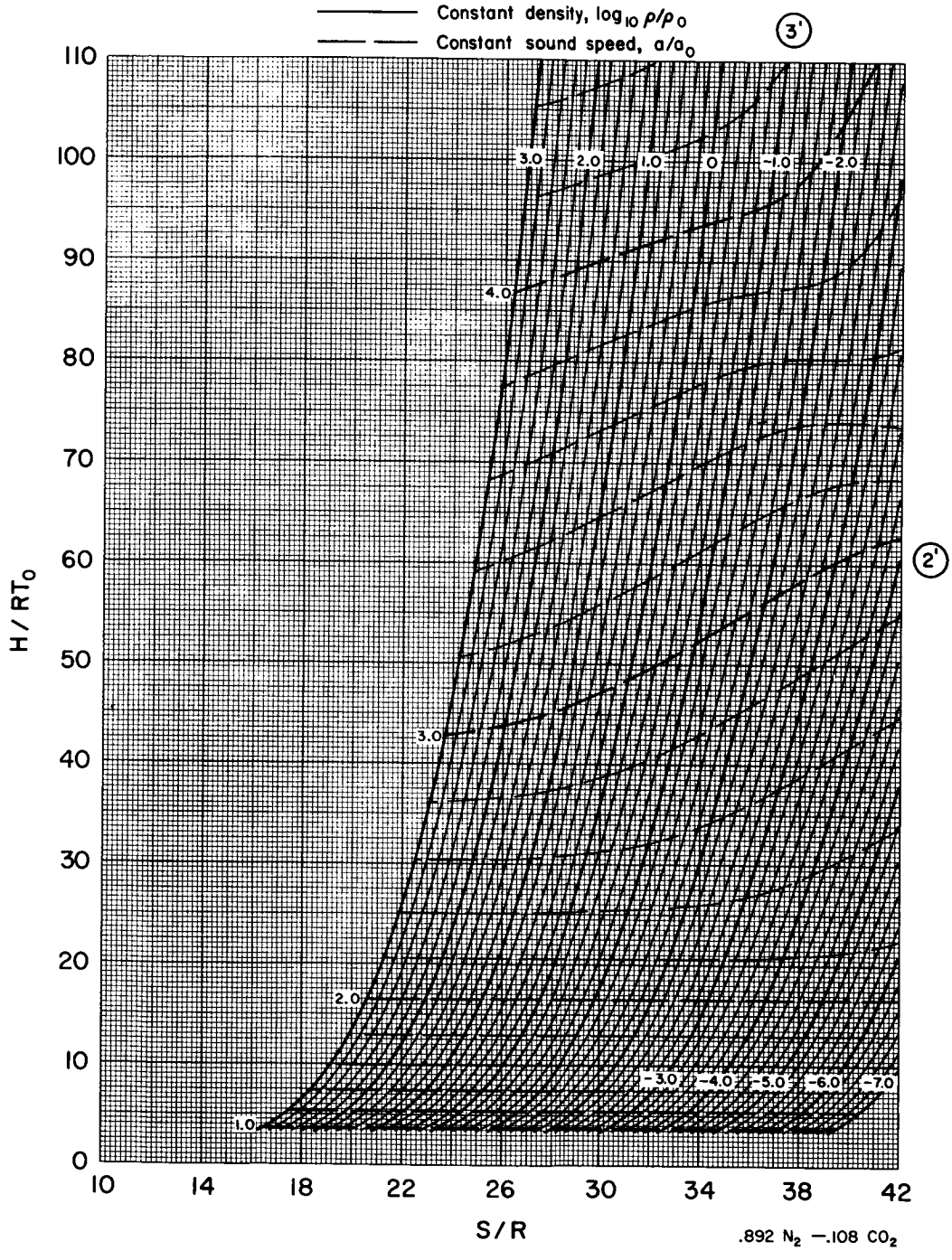


Figure 10. - Key to presentation of thermodynamic data.



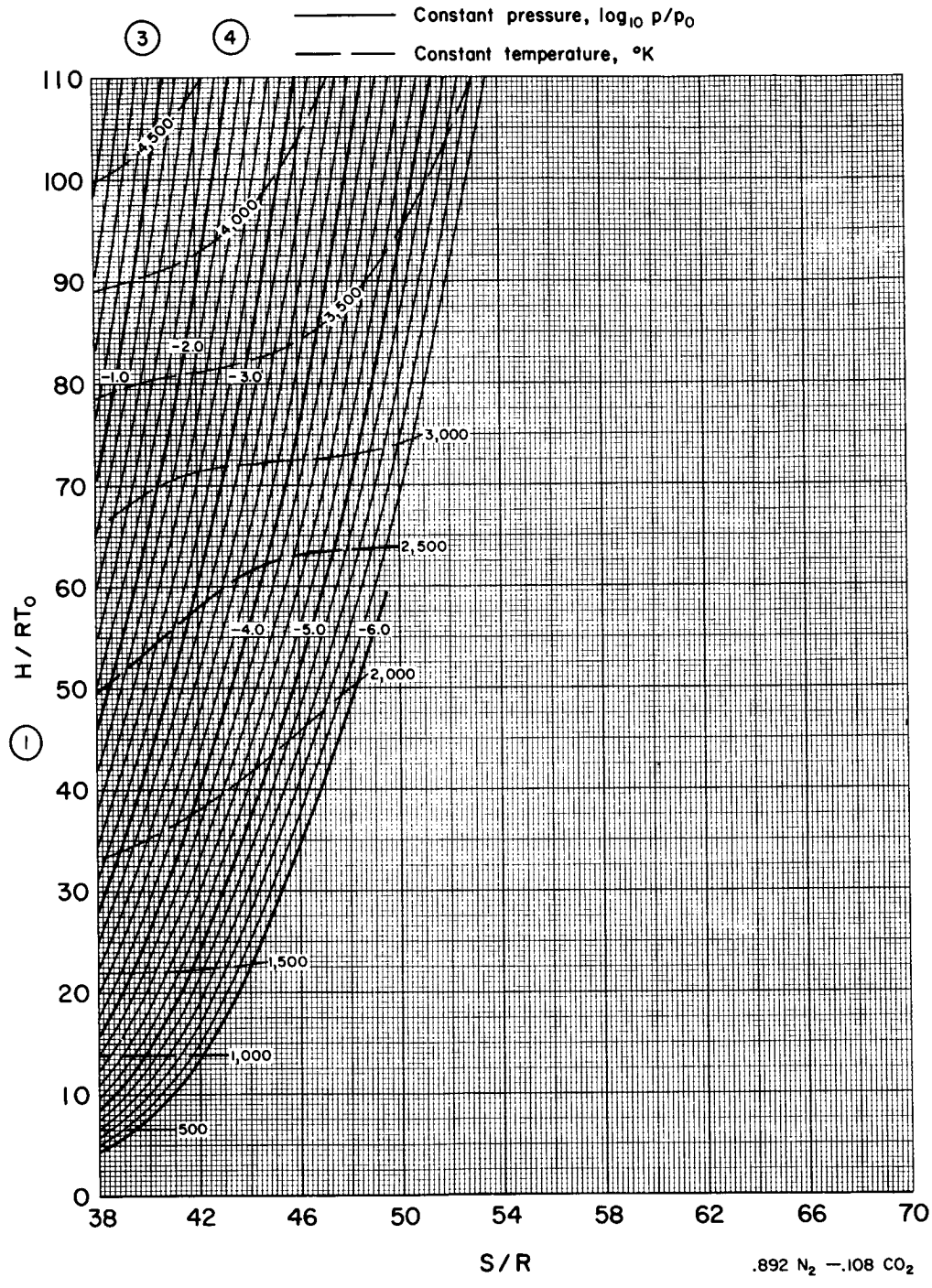
(a) Region 1.

Figure 11. - Thermodynamic data.



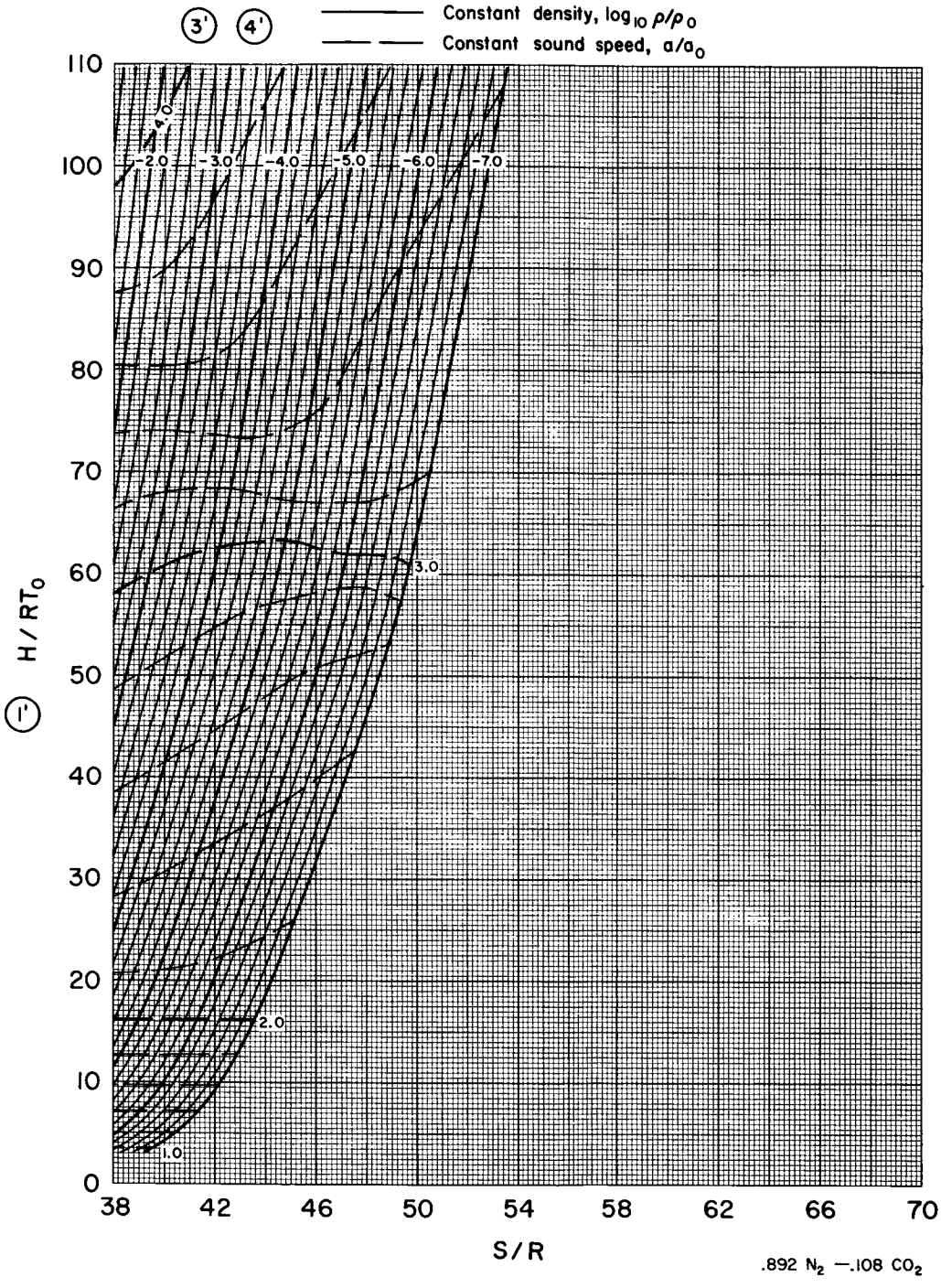
(a) Region 1 - Concluded.

Figure 11. - Continued.



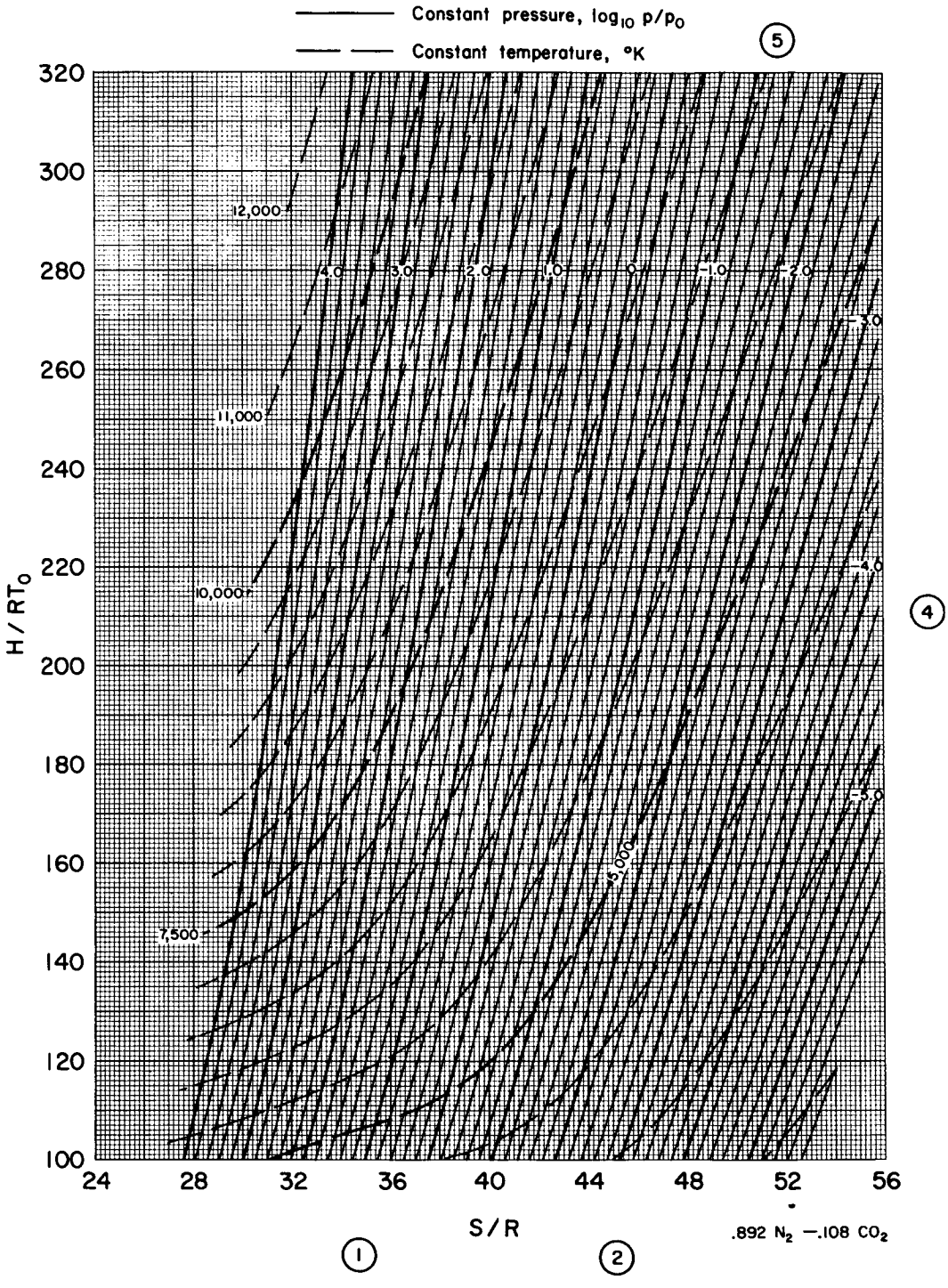
(b) Region 2.

Figure 11. - Continued.



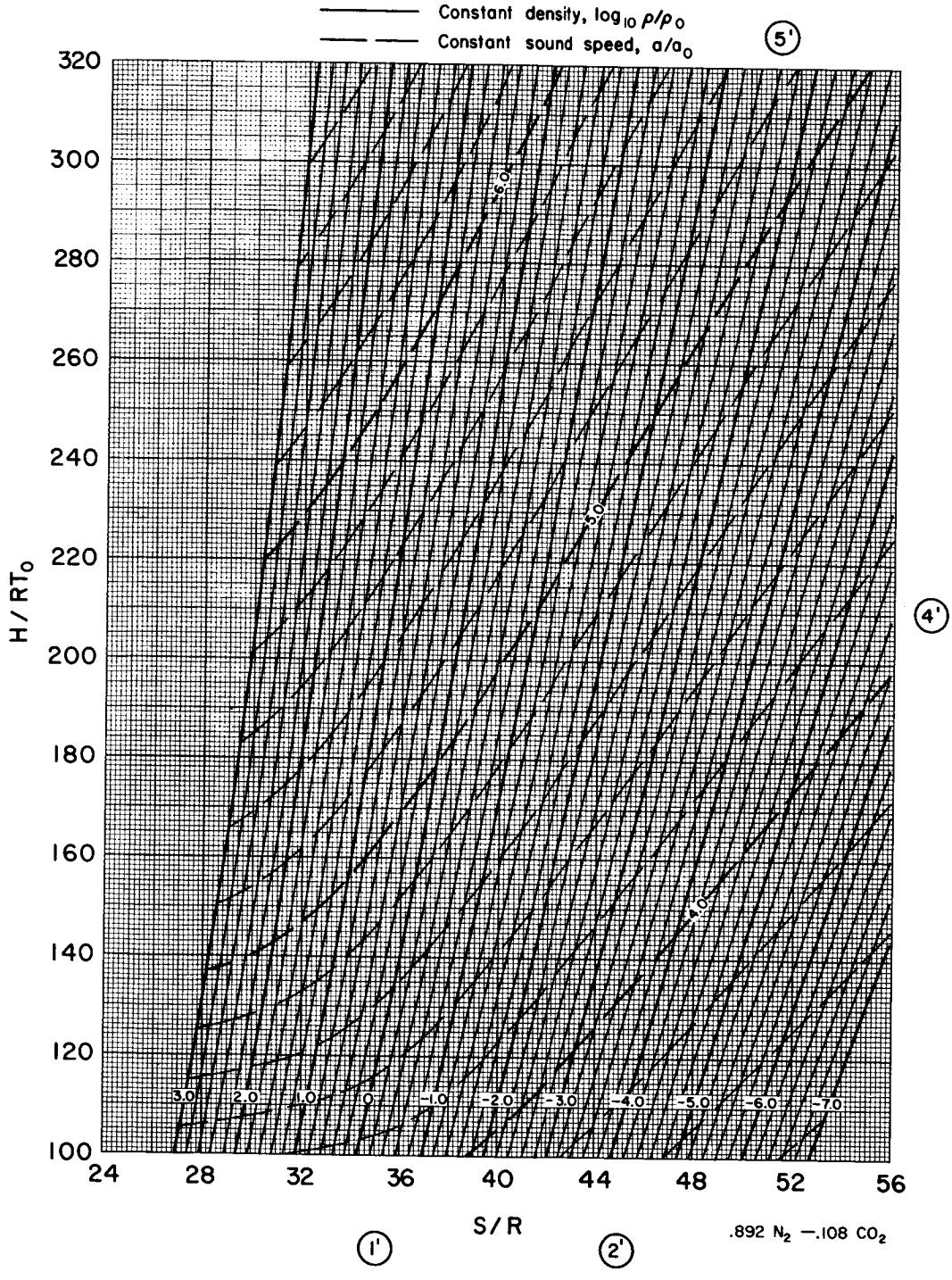
(b) Region 2 - Concluded.

Figure 11. - Continued.



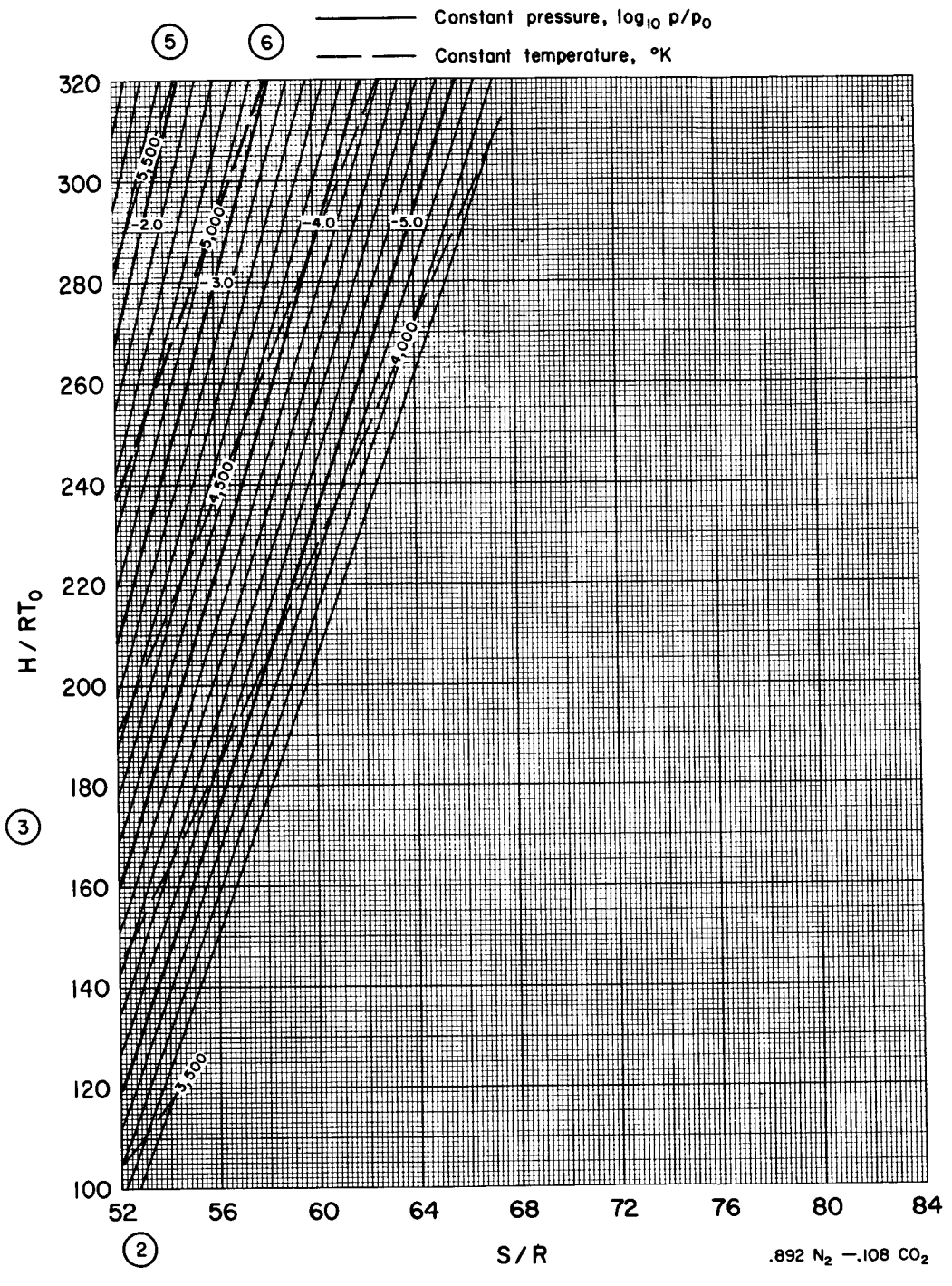
(c) Region 3.

Figure 11. - Continued.



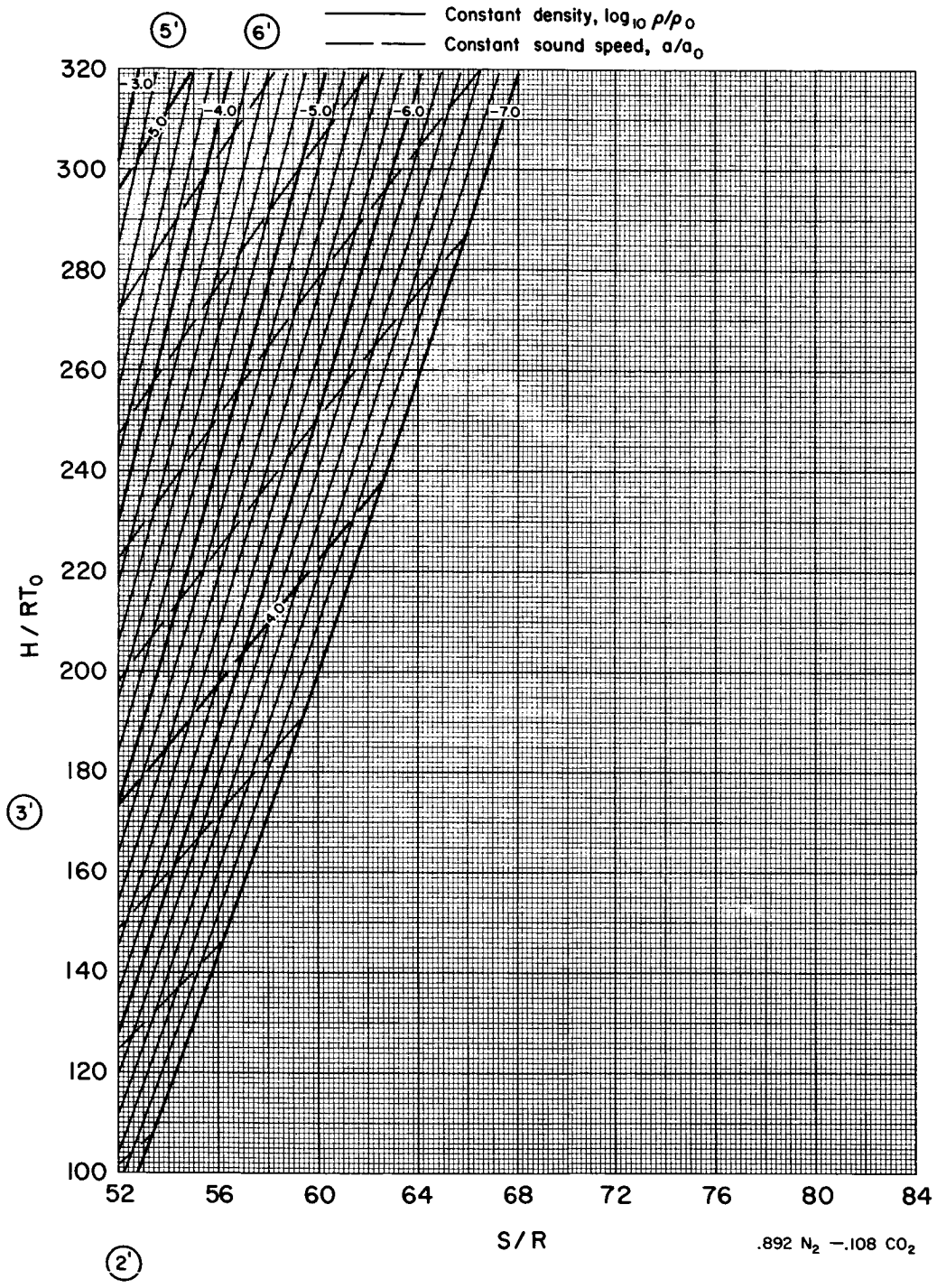
(c) Region 3 - Concluded.

Figure 11. - Continued.



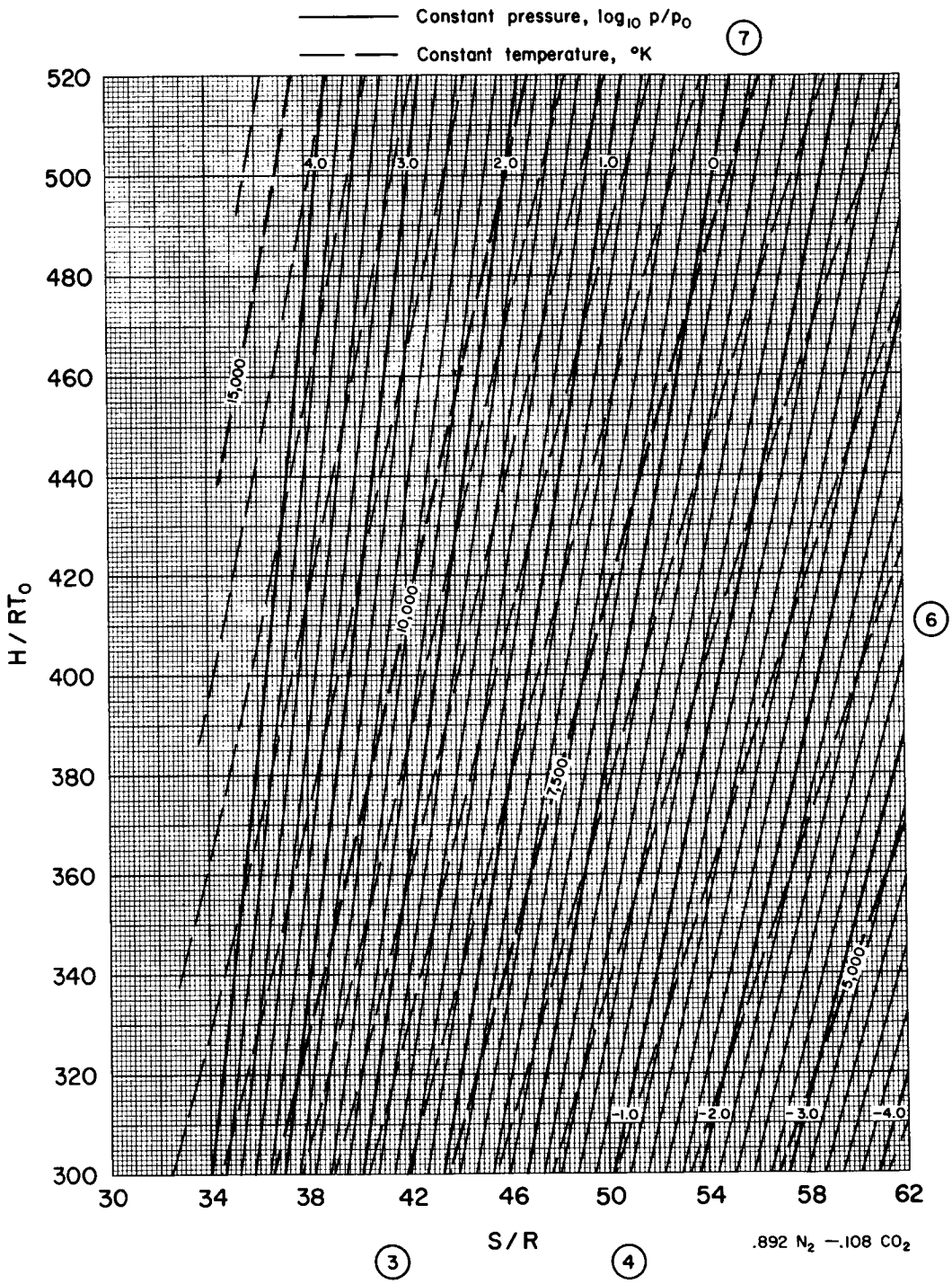
(d) Region 4.

Figure 11. - Continued.



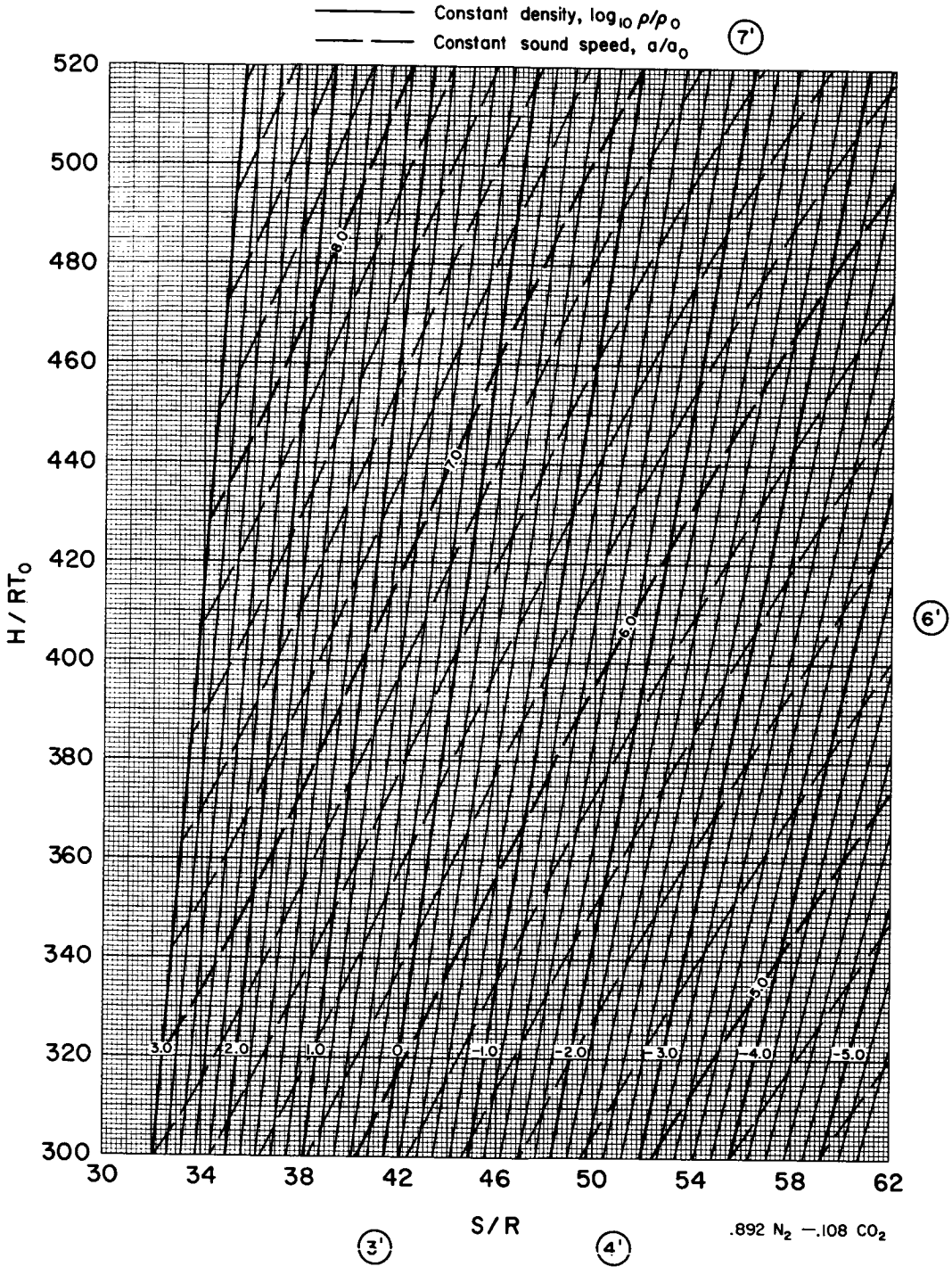
(d) Region 4 - Concluded.

Figure 11. - Continued.



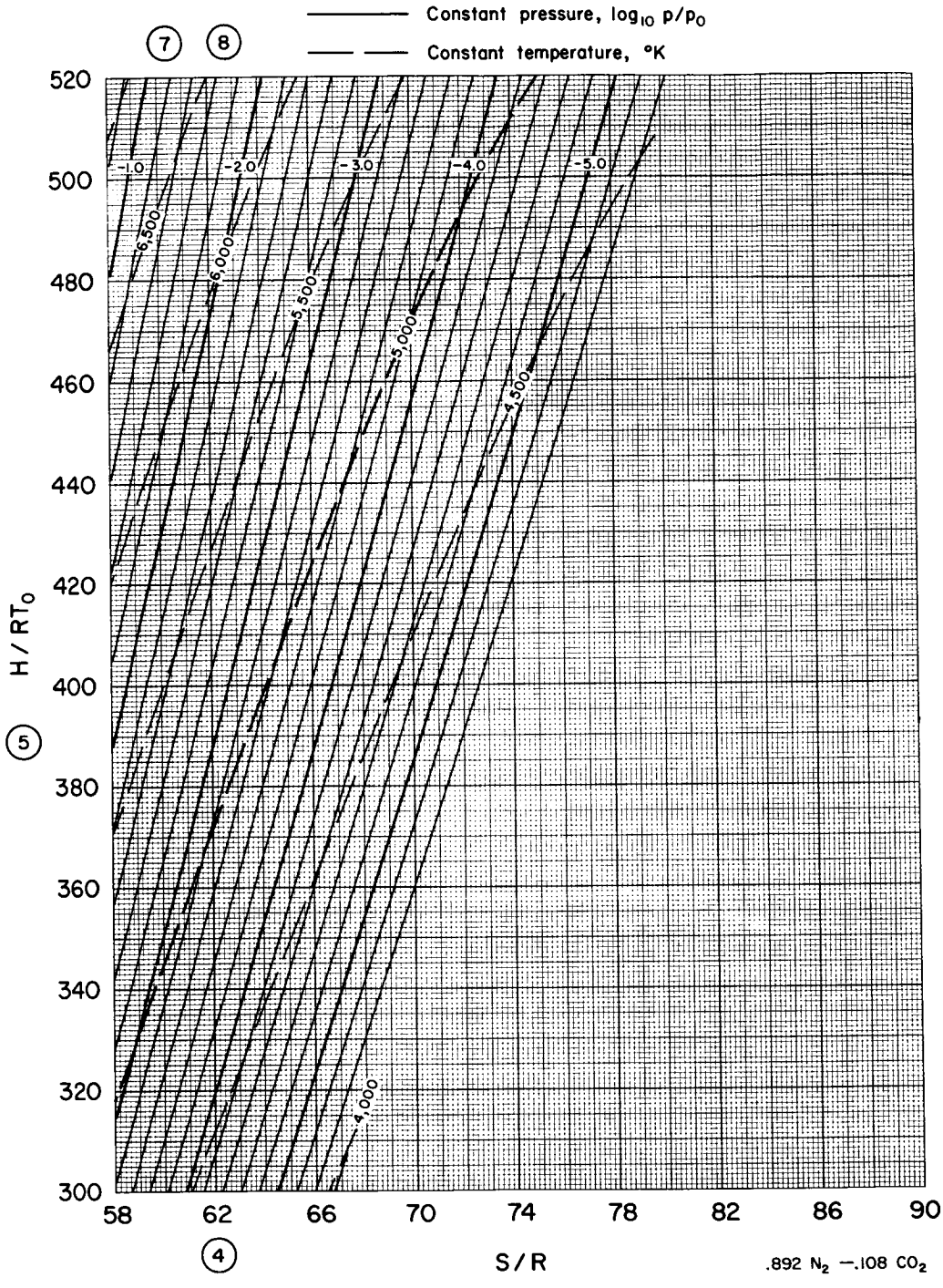
(e) Region 5.

Figure 11. - Continued.



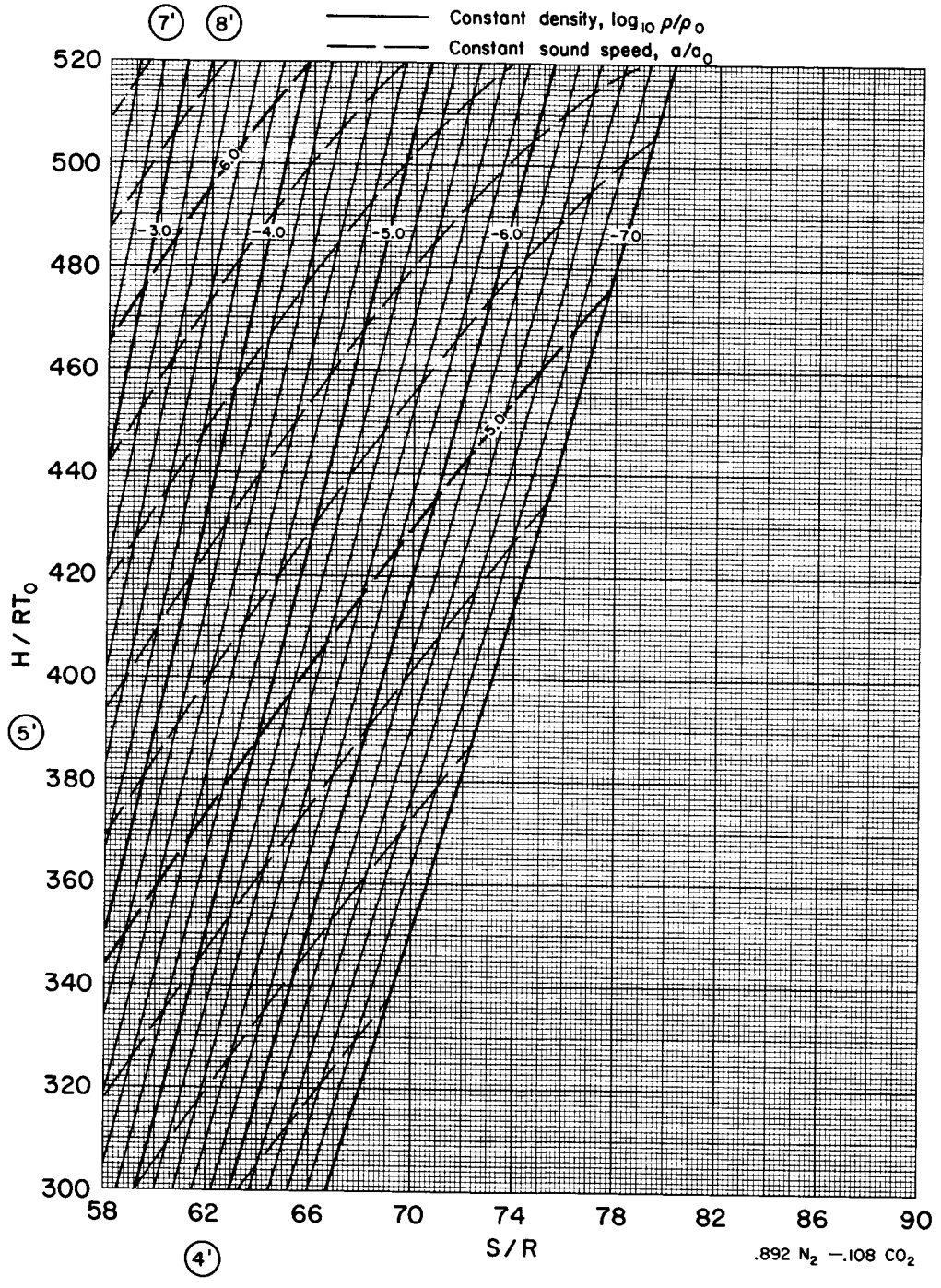
(e) Region 5 - Concluded.

Figure 11. - Continued.



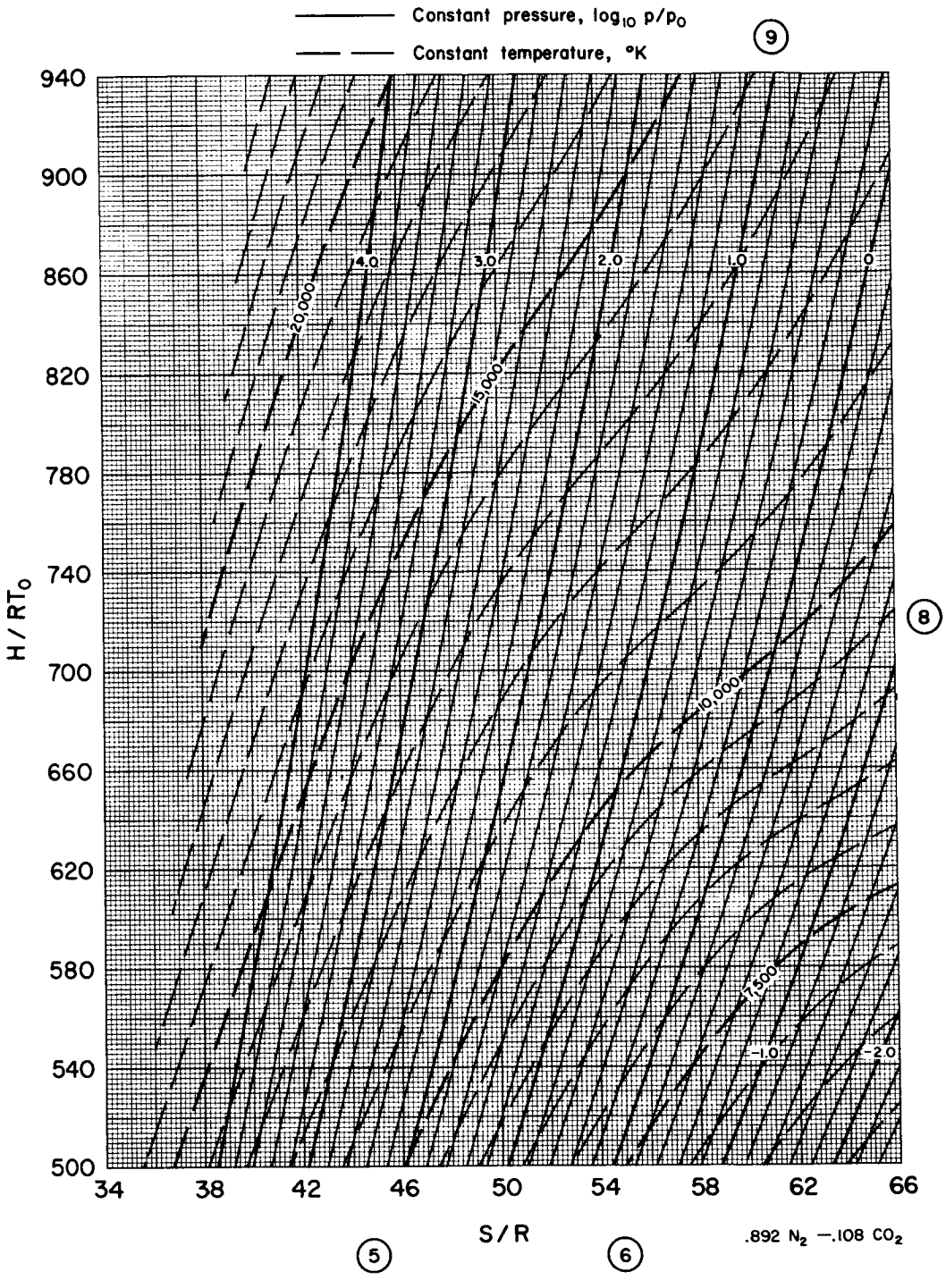
(f) Region 6.

Figure 11. - Continued.



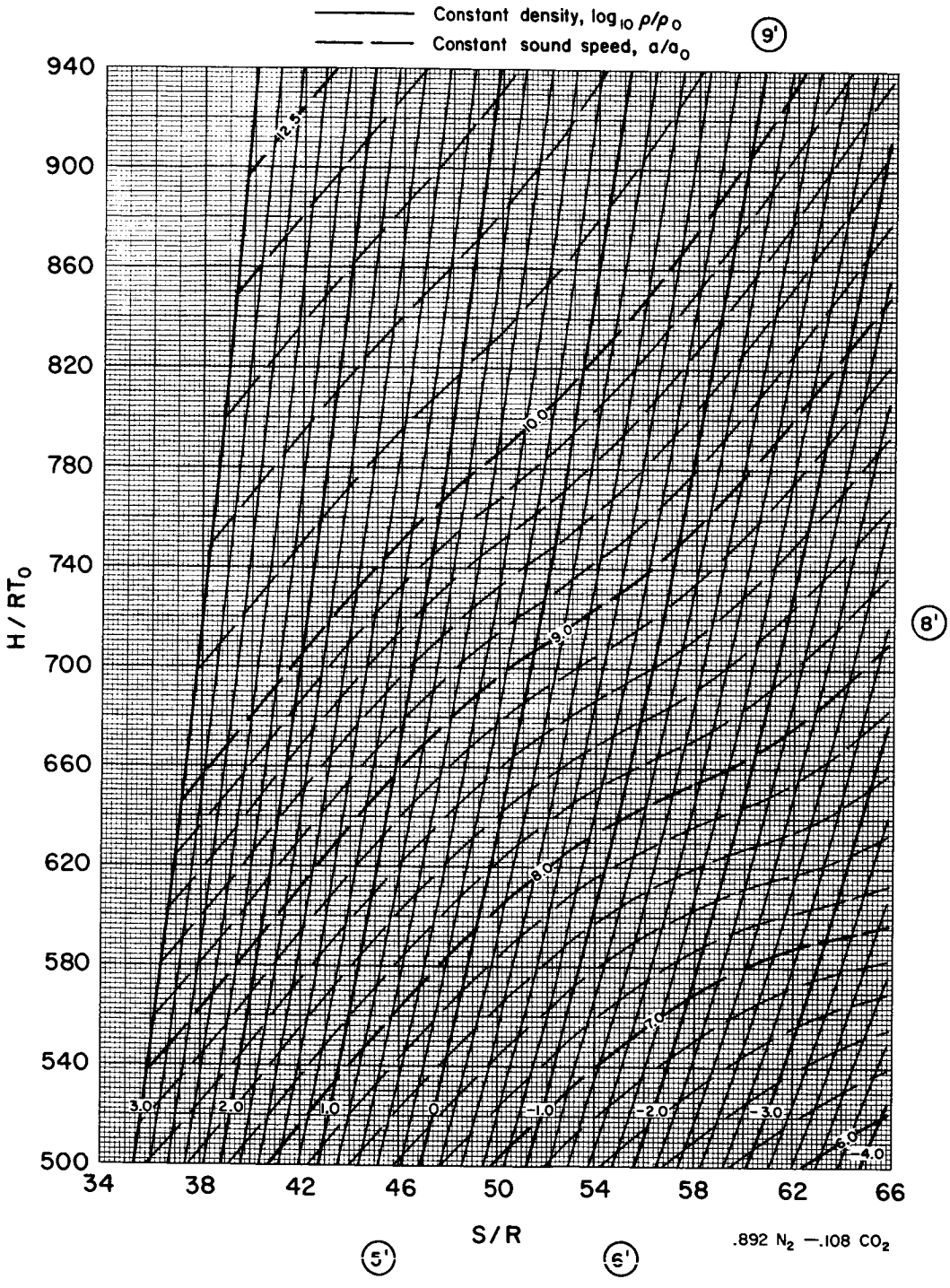
(f) Region 6 - Concluded.

Figure 11. - Continued.



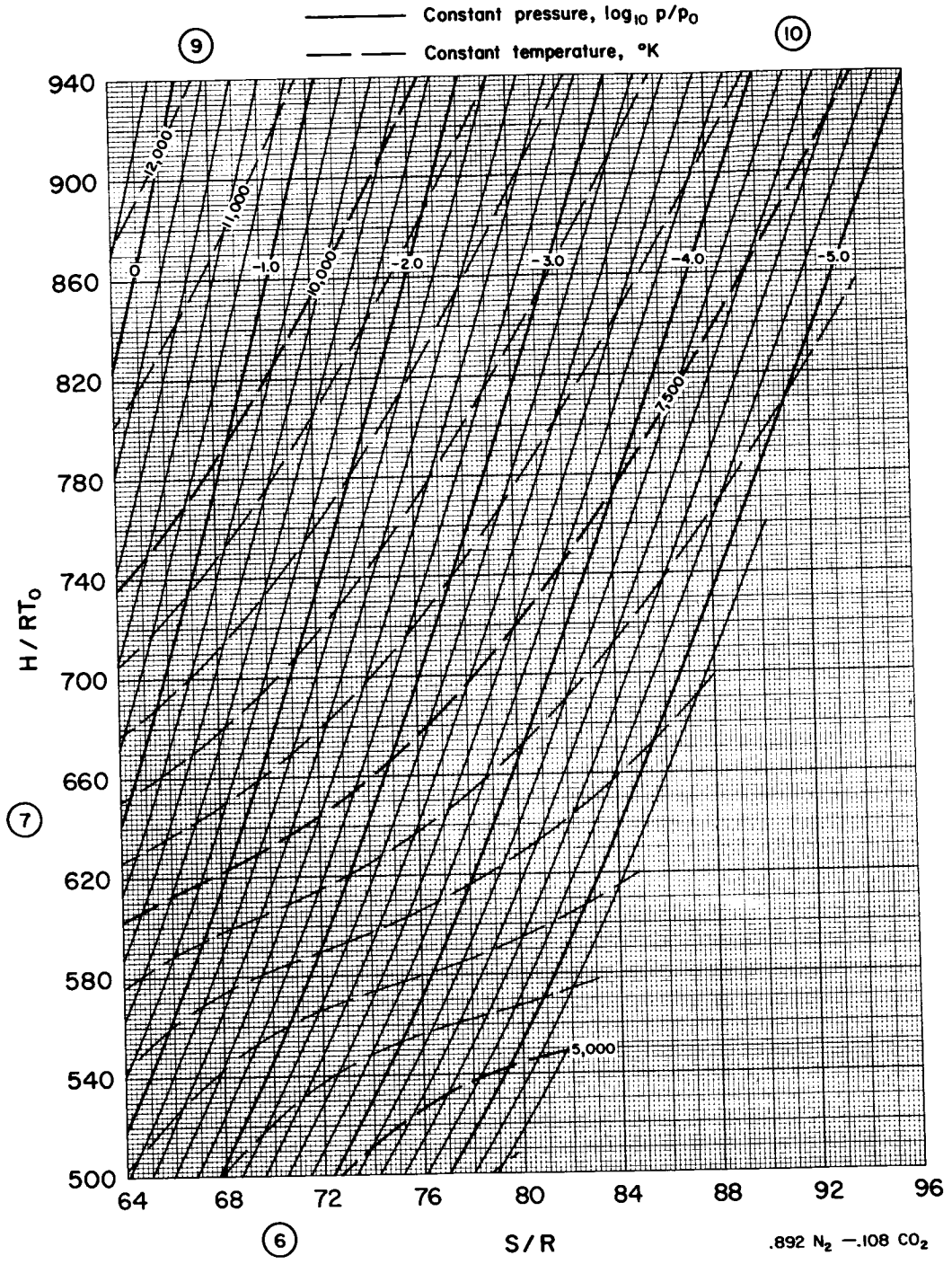
(g) Region 7.

Figure 11. - Continued.



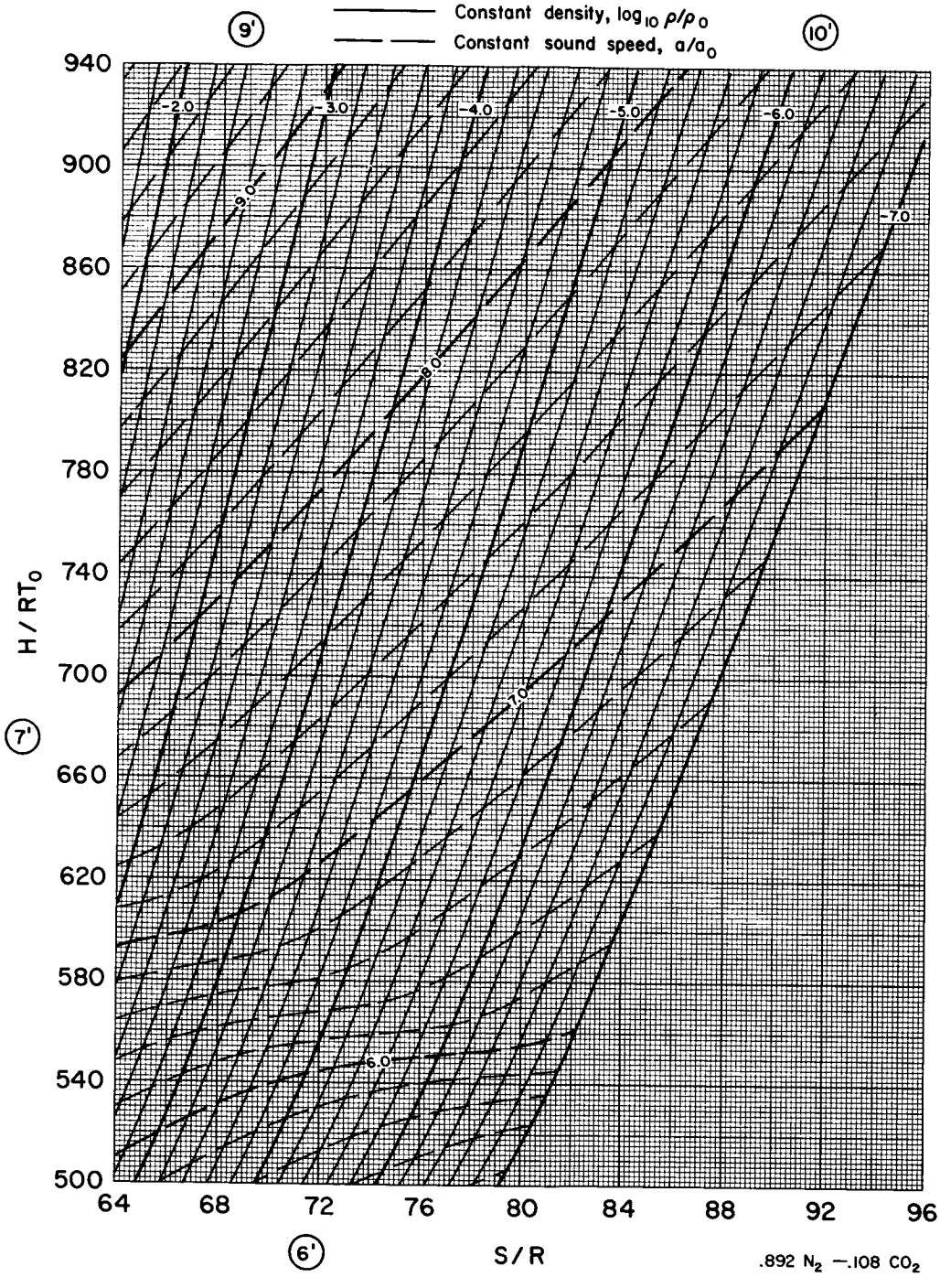
(g) Region 7 - Concluded.

Figure 11. - Continued.



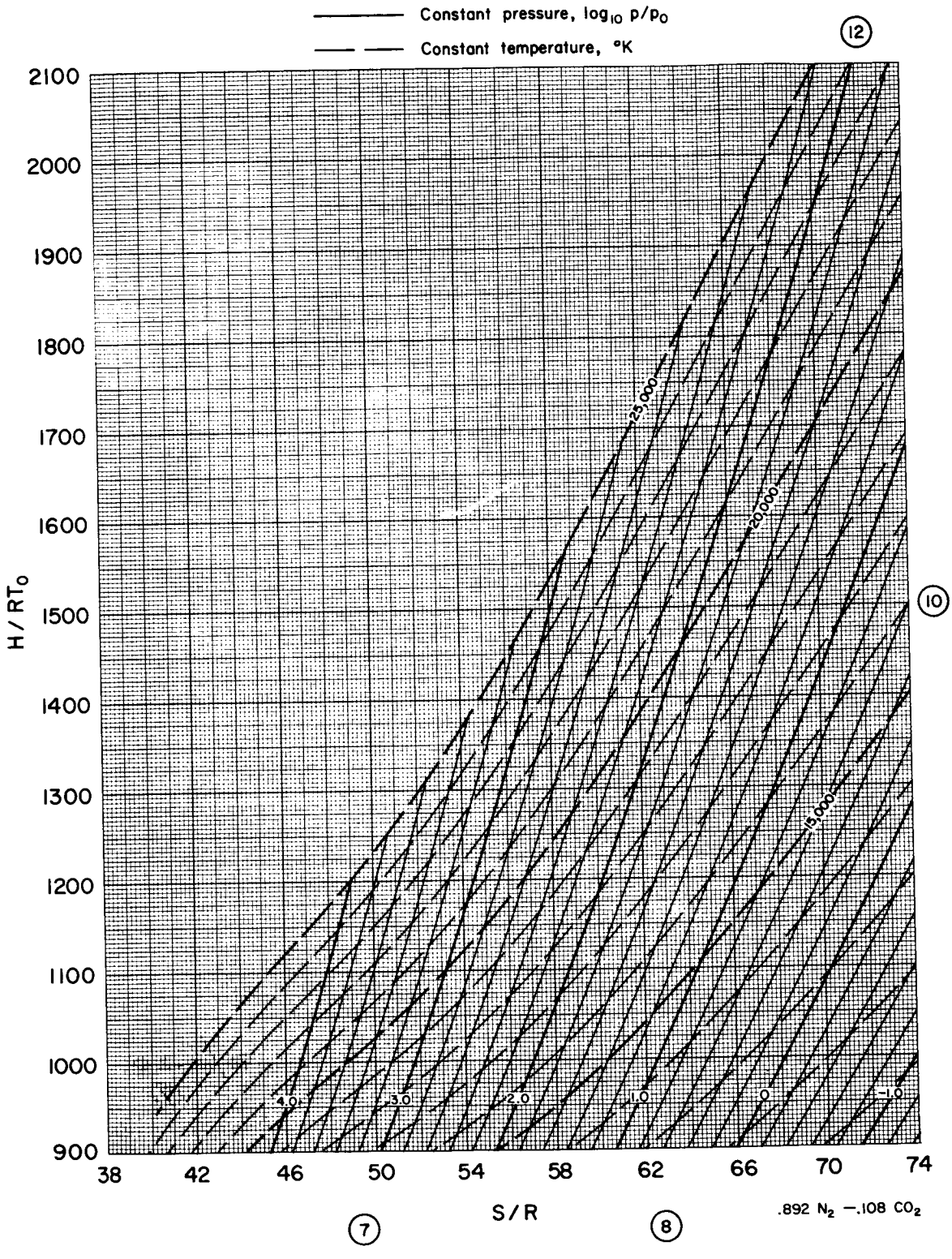
(h) Region 8

Figure 11. - Continued.



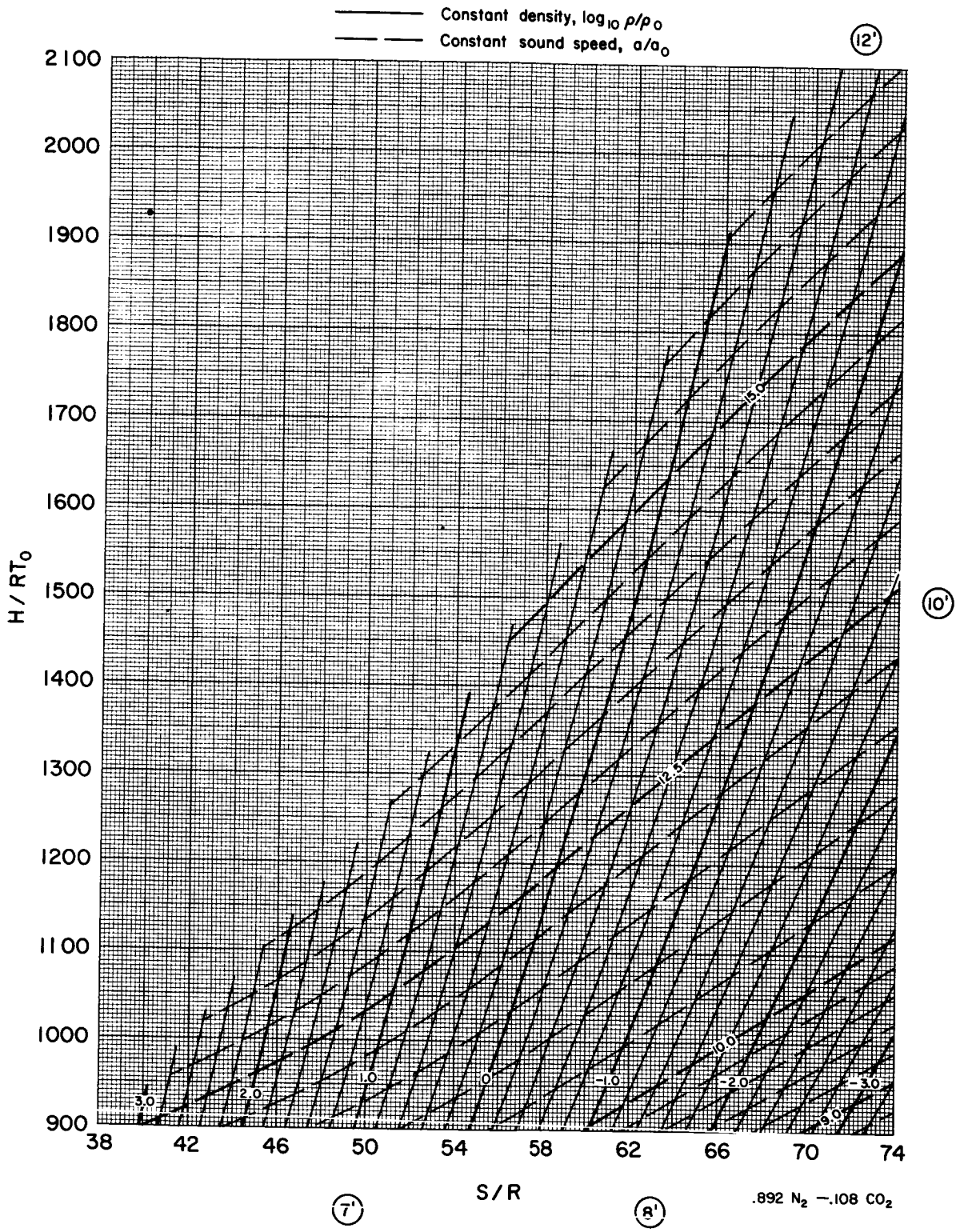
(h) Region 8 - Concluded.

Figure 11. - Continued.



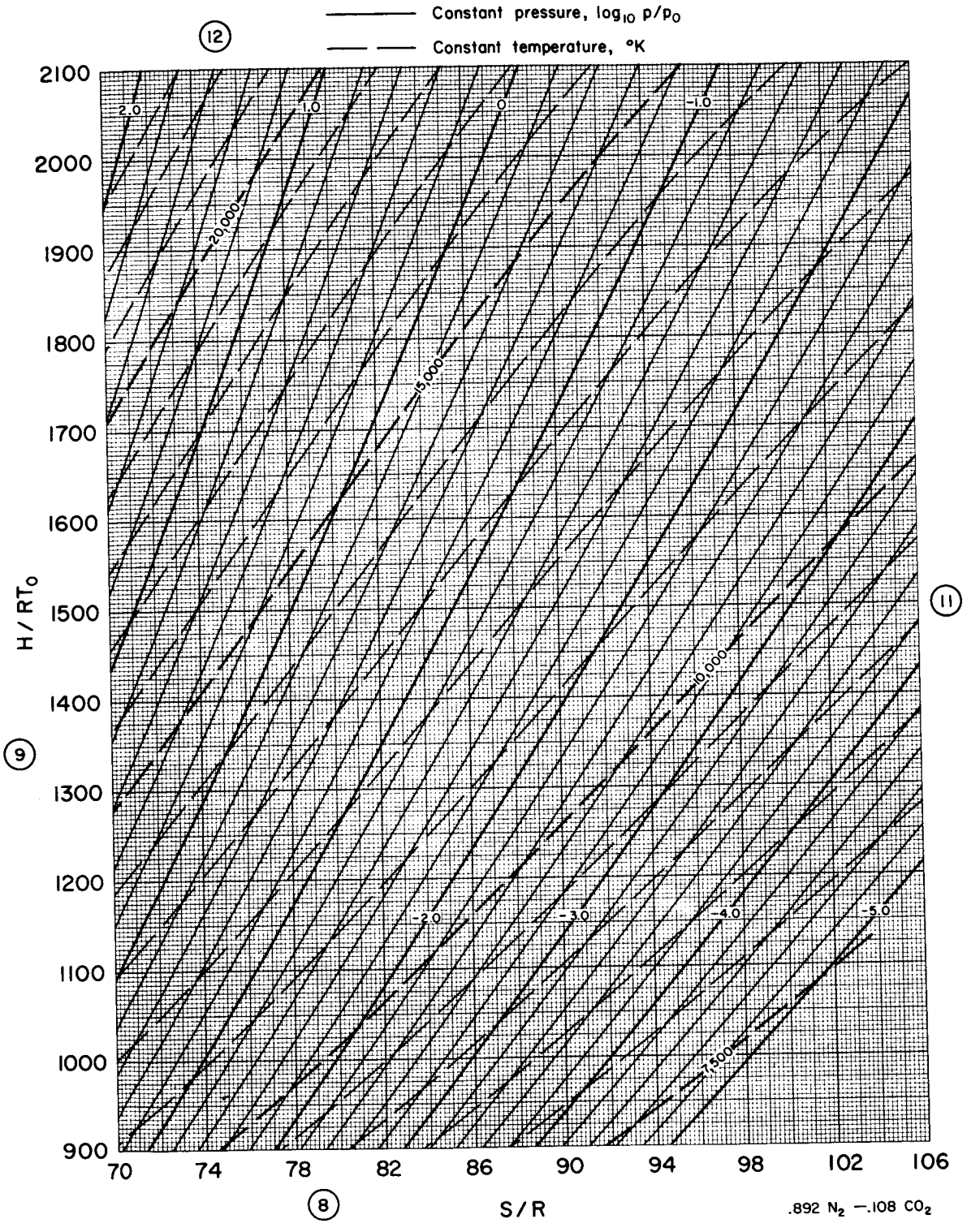
(i) Region 9.

Figure 11. - Continued.



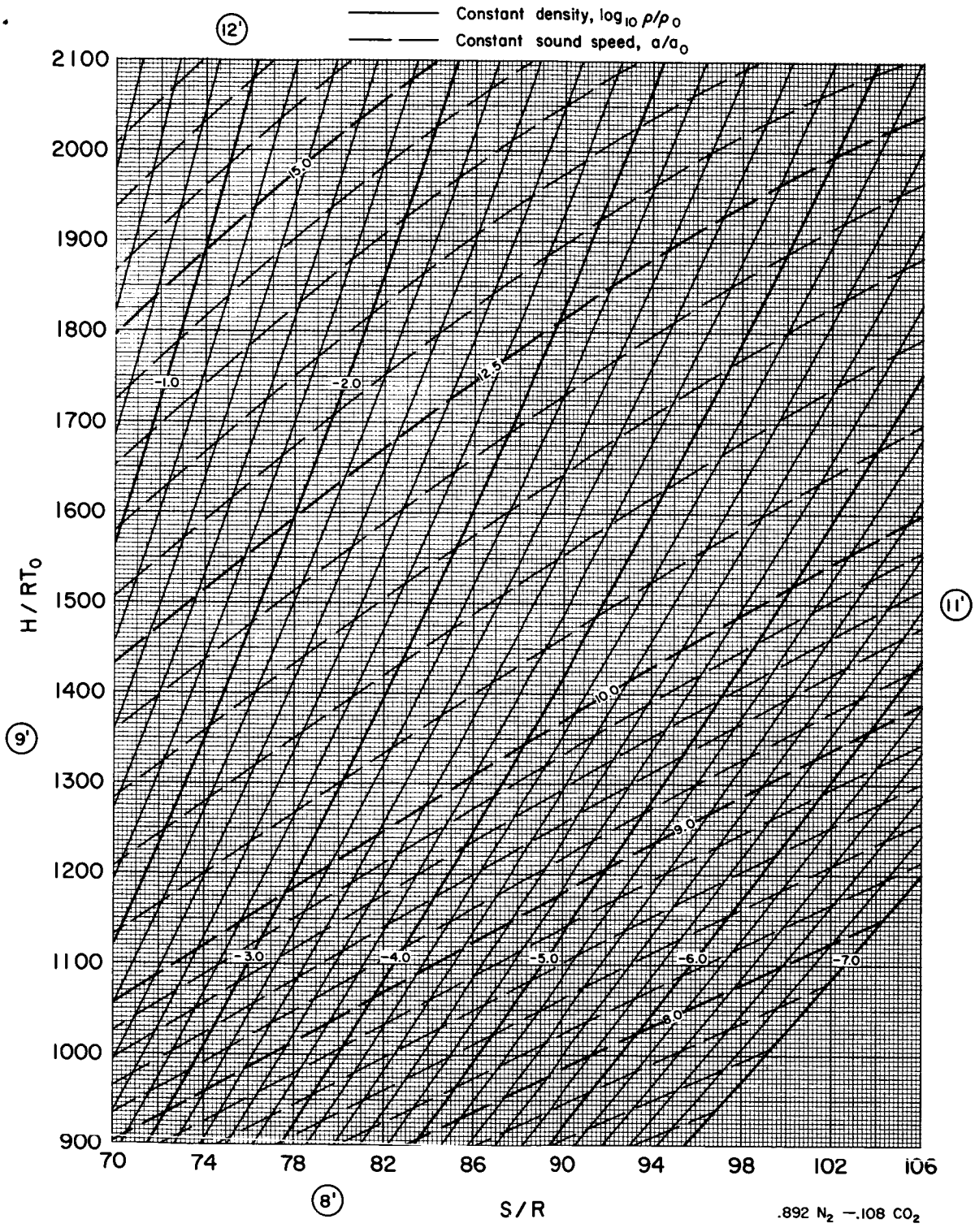
(i) Region 9 - Concluded.

Figure 11. - Continued.



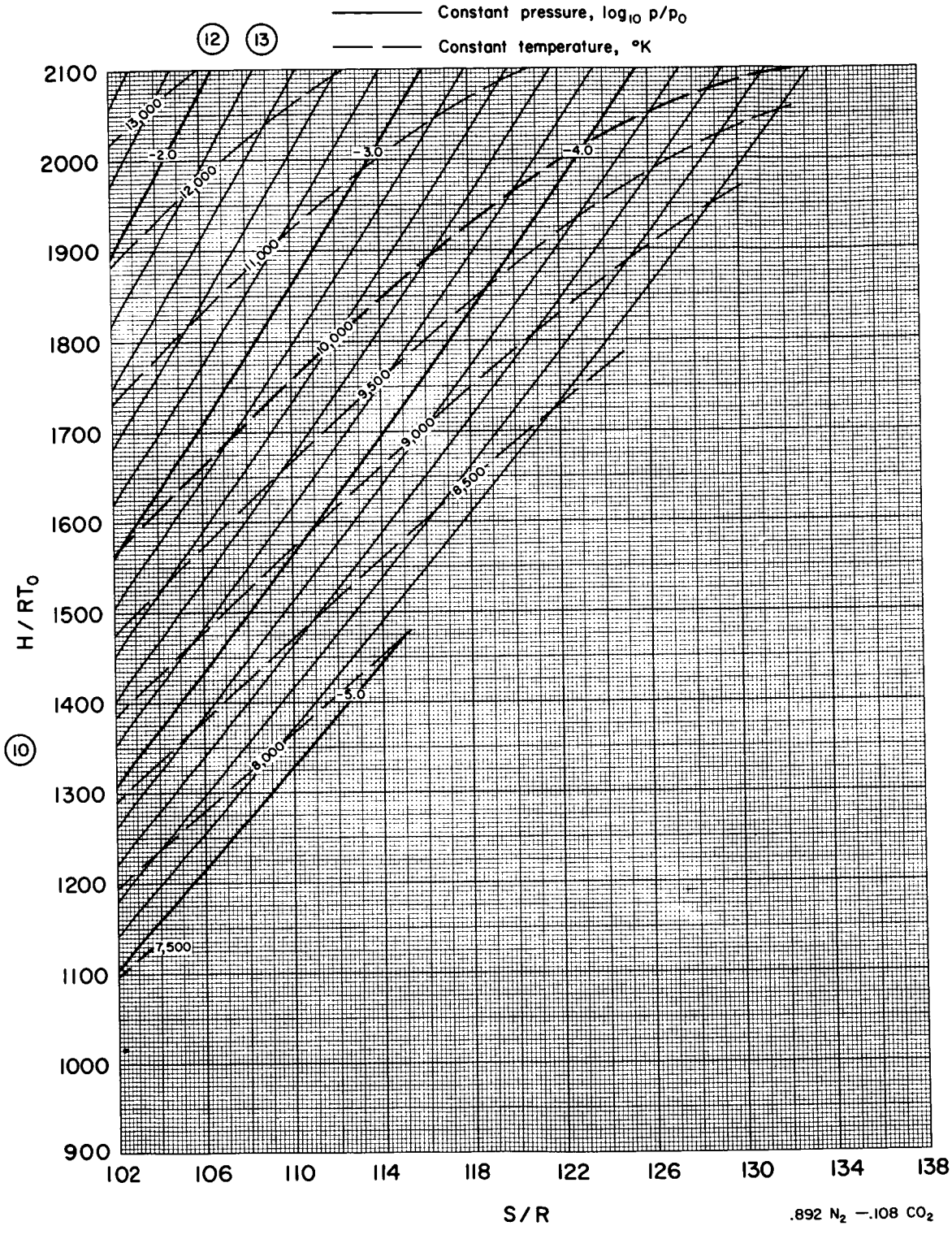
(j) Region 10.

Figure 11. - Continued.



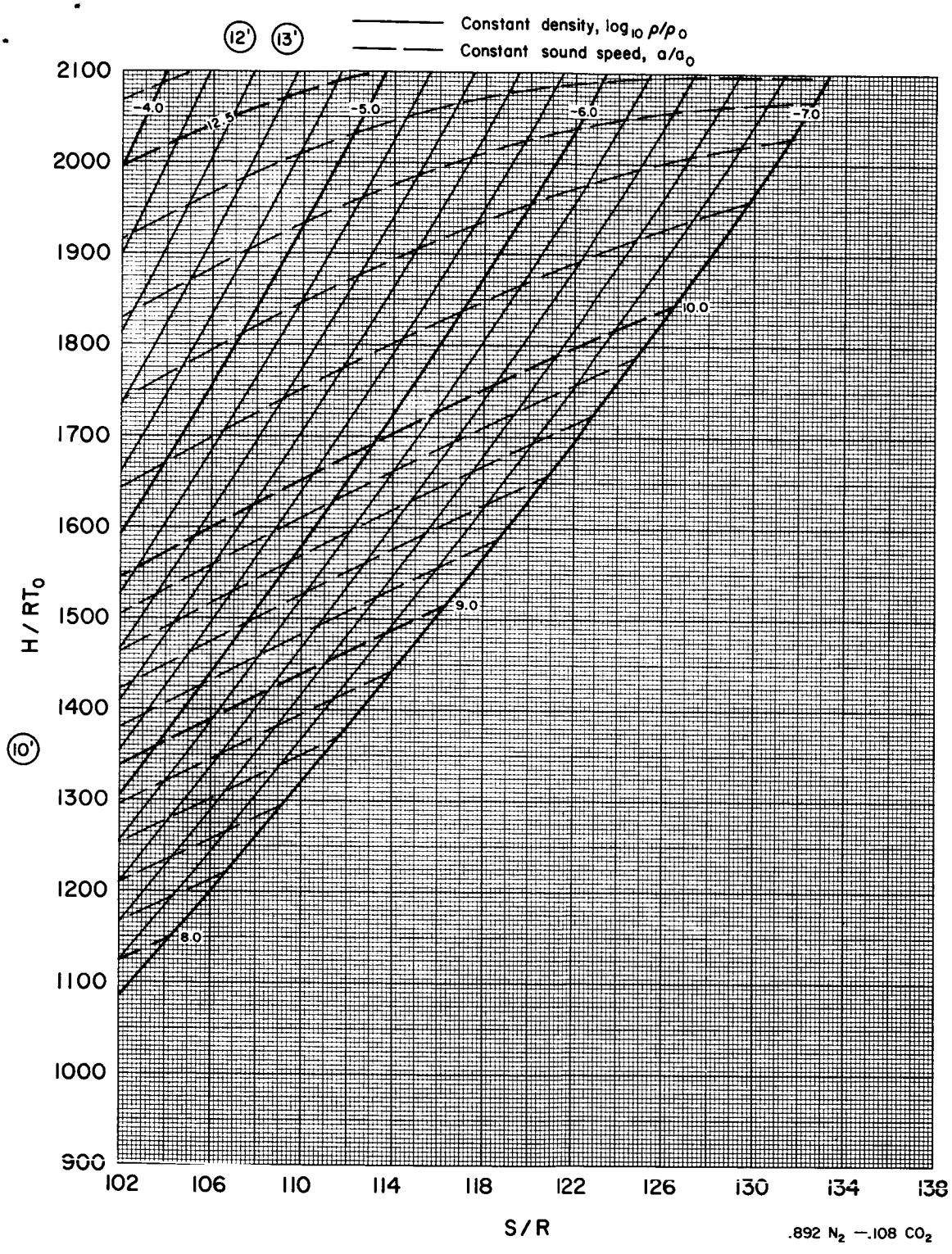
(j) Region 10 - Concluded.

Figure 11. - Continued.



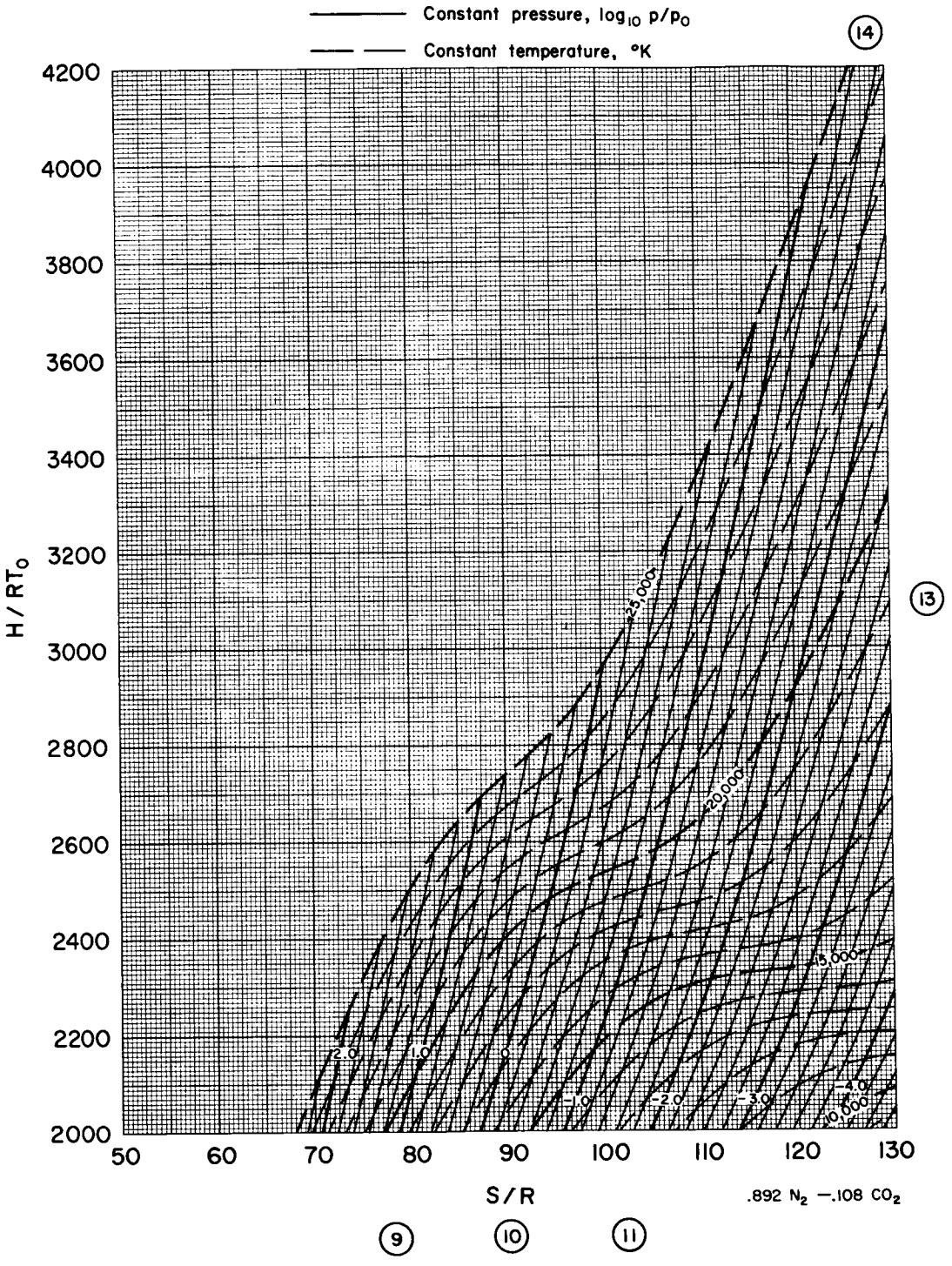
(k) Region 11.

Figure 11. - Continued.



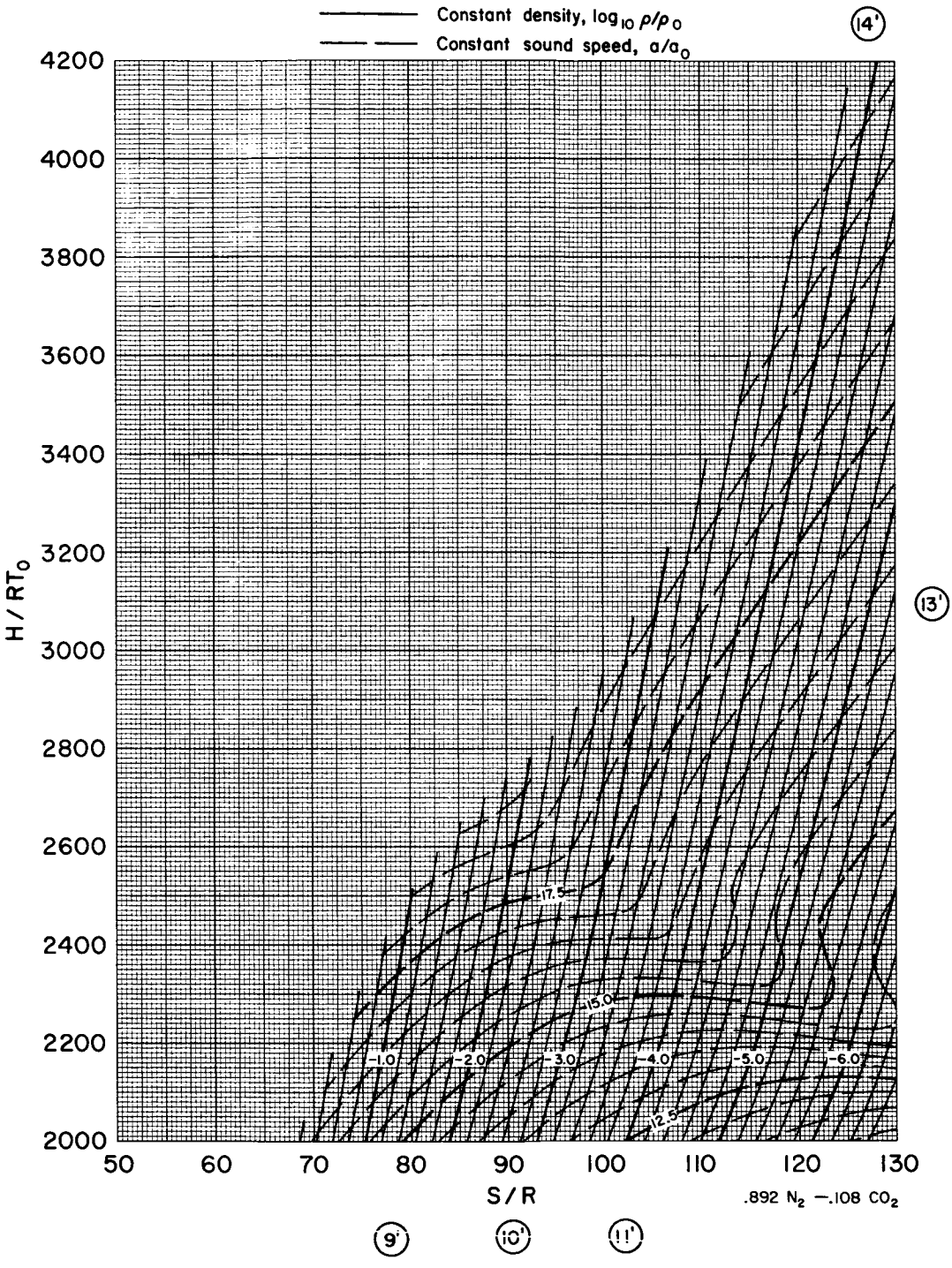
(k) Region 11 - Concluded.

Figure 11. - Continued.



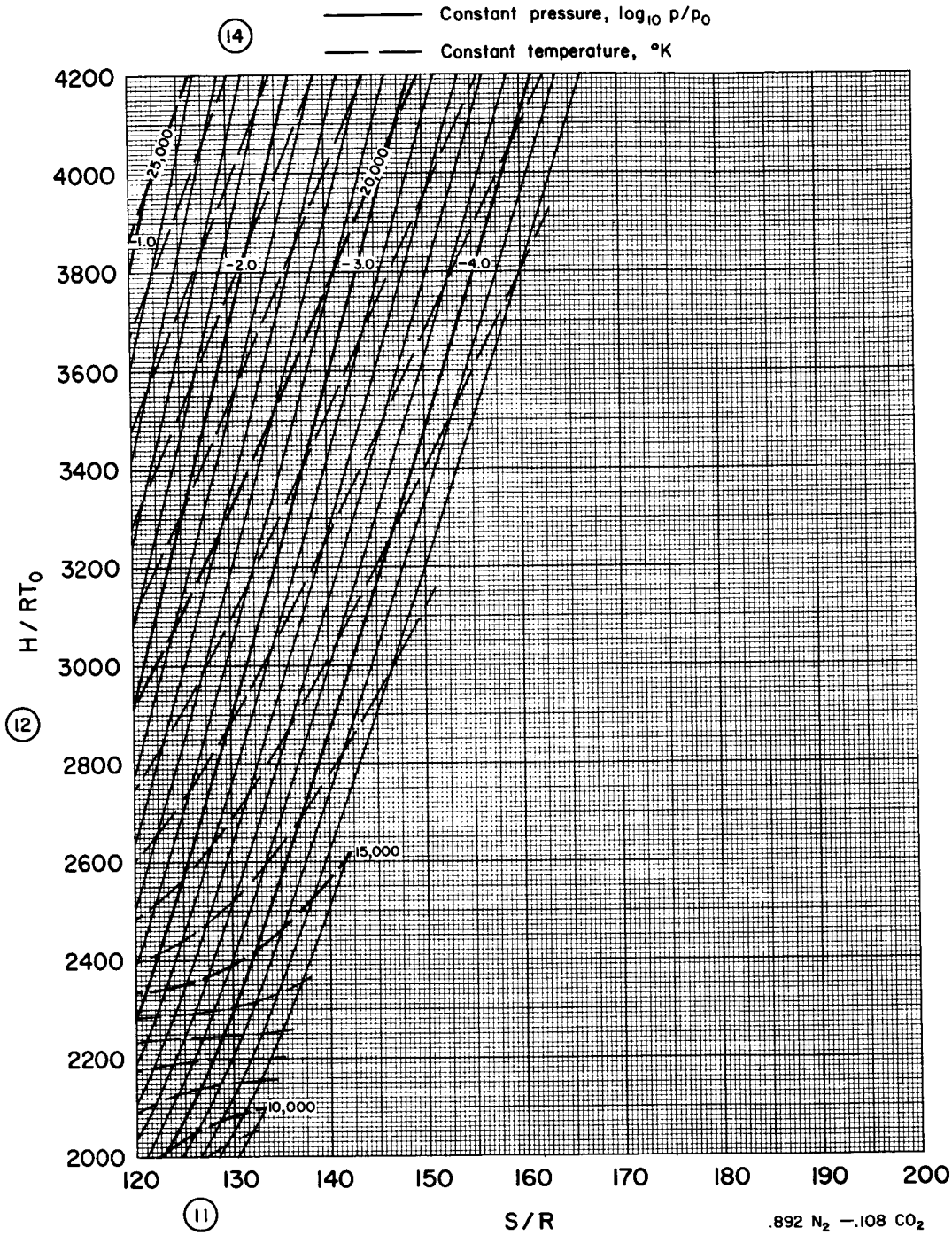
(l) Region 12.

Figure 11. - Continued.



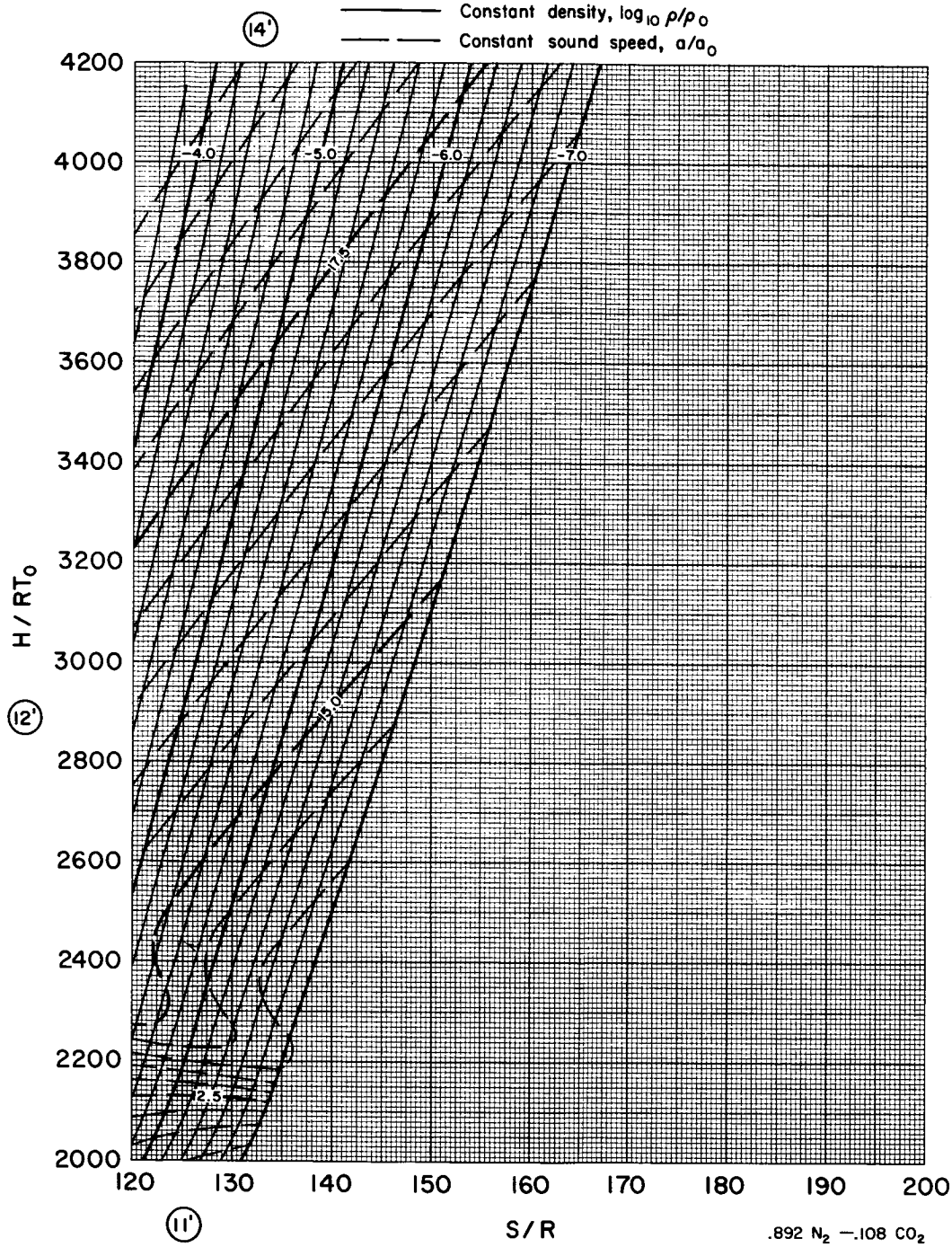
(*l*) Region 12 - Concluded.

Figure 11. - Continued.



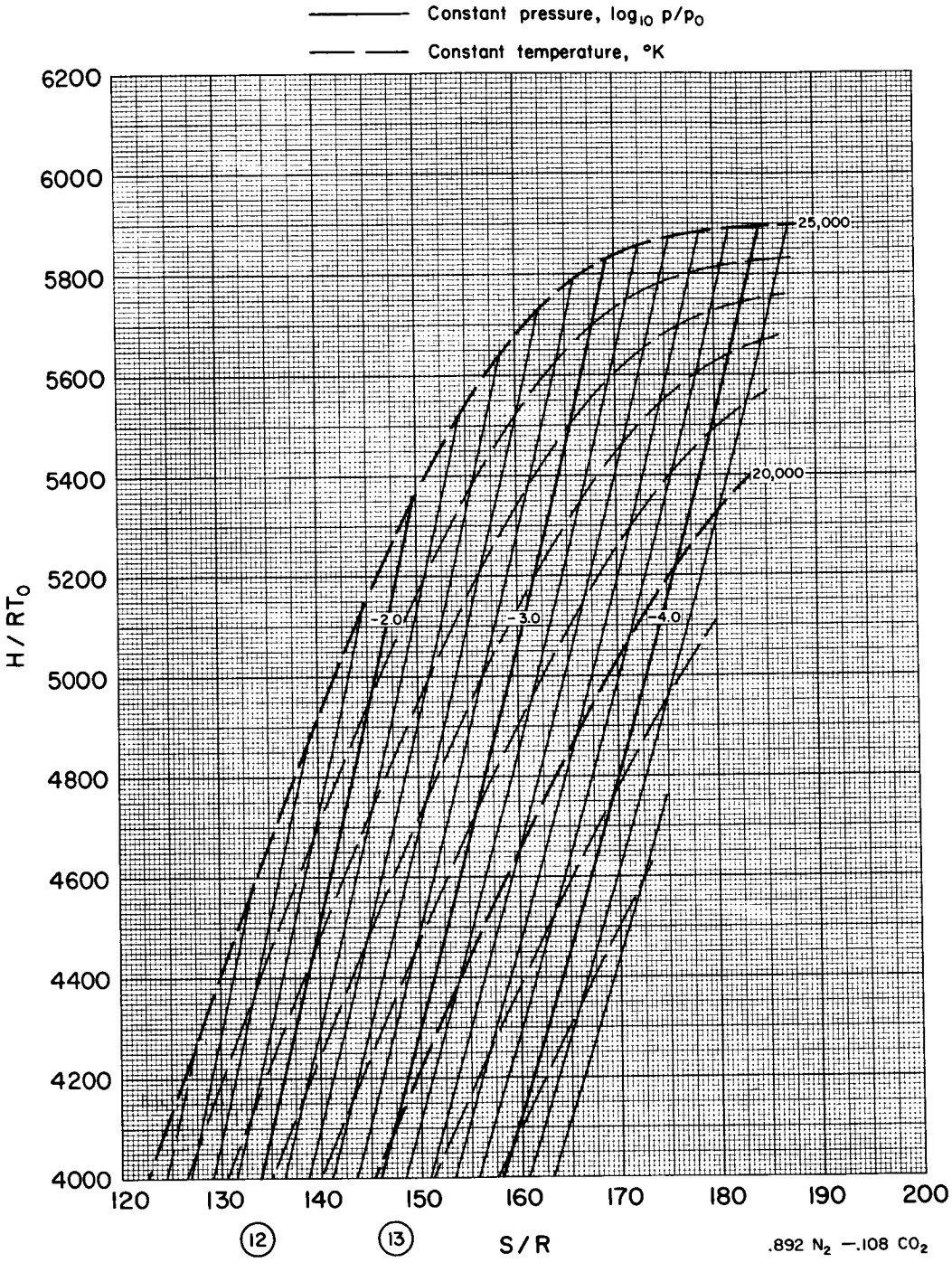
(m) Region 13.

Figure 11. - Continued.



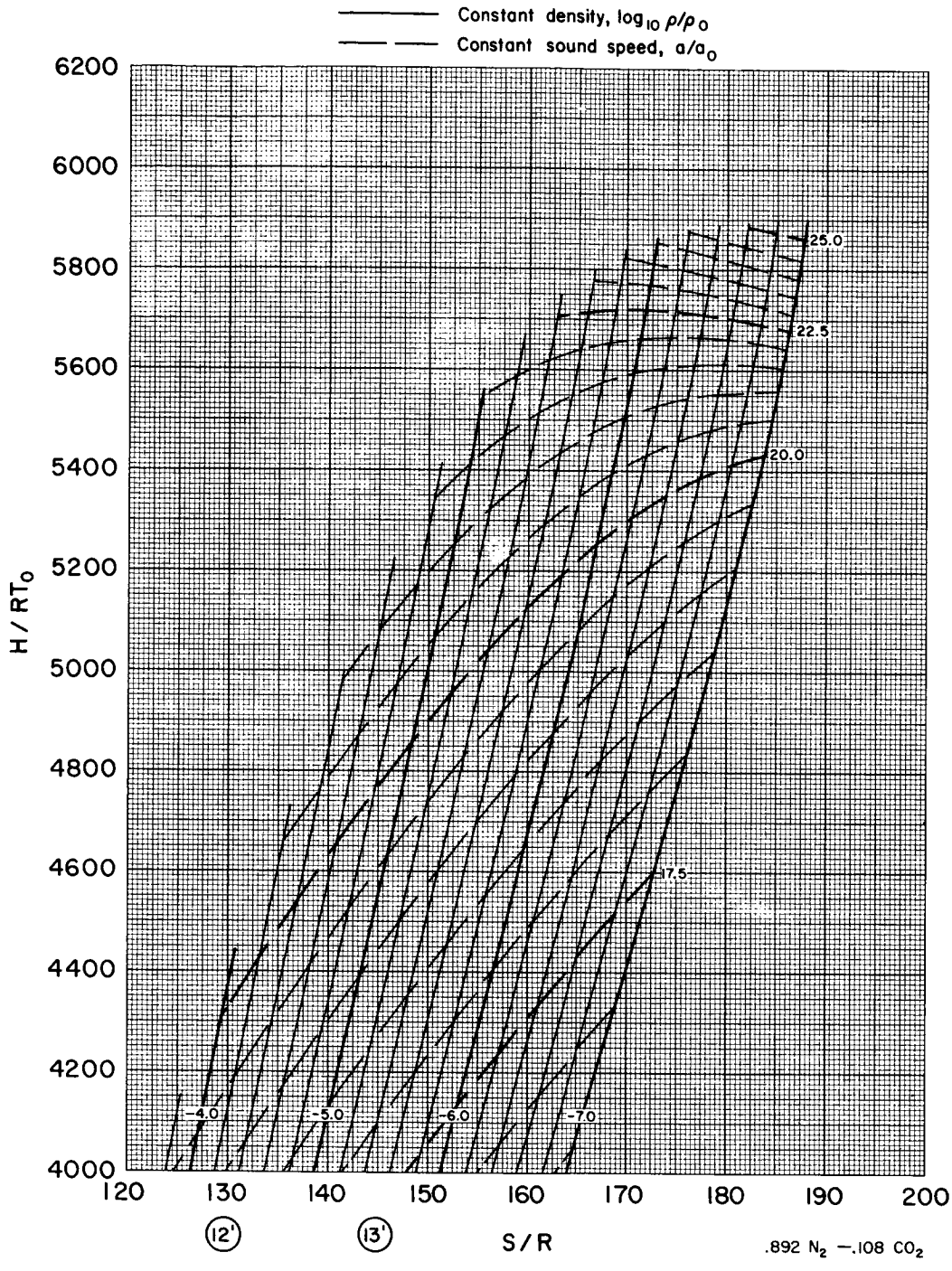
(m) Region 13 - Concluded.

Figure 11. - Continued.



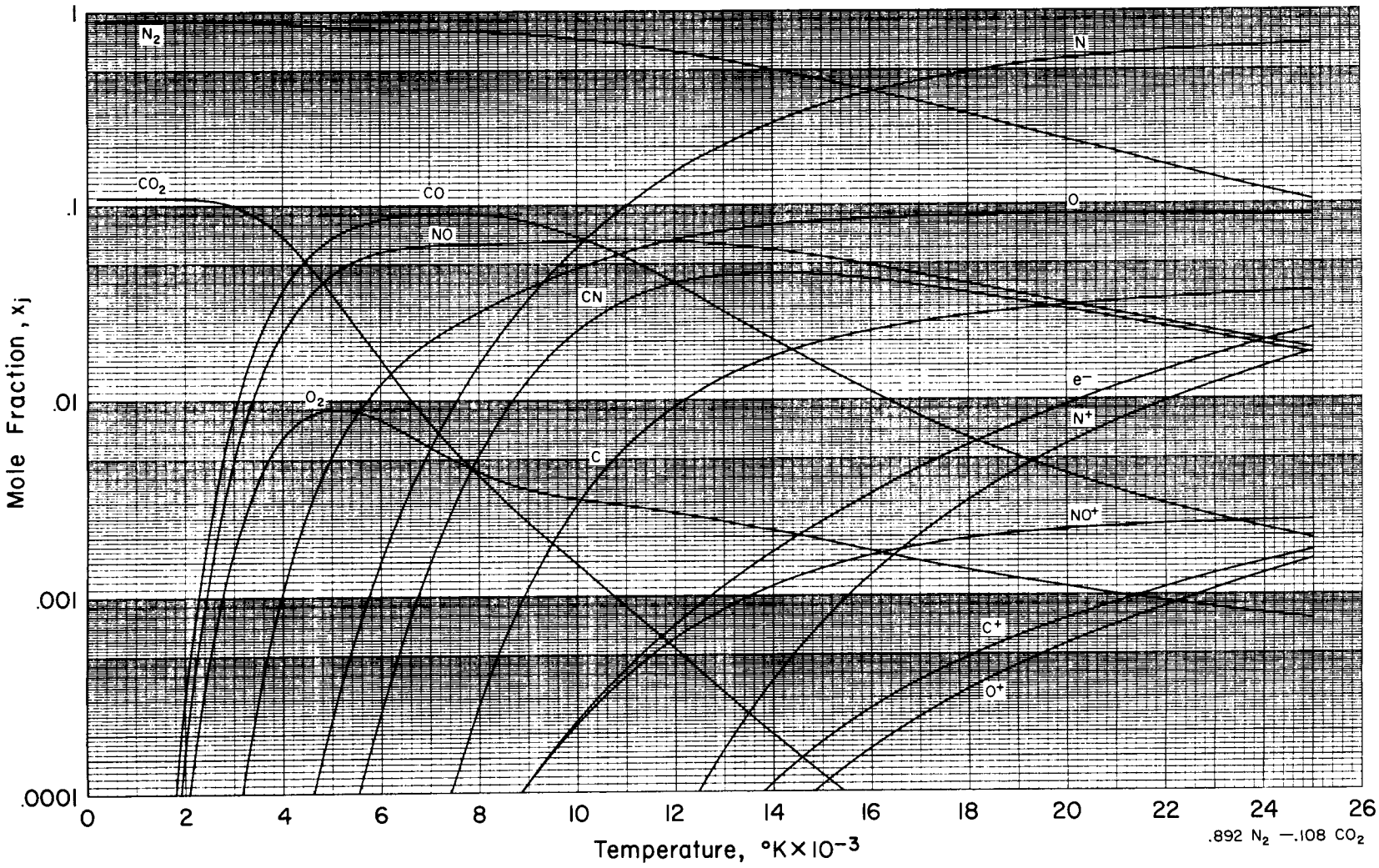
(n) Region 14.

Figure 11. - Continued.



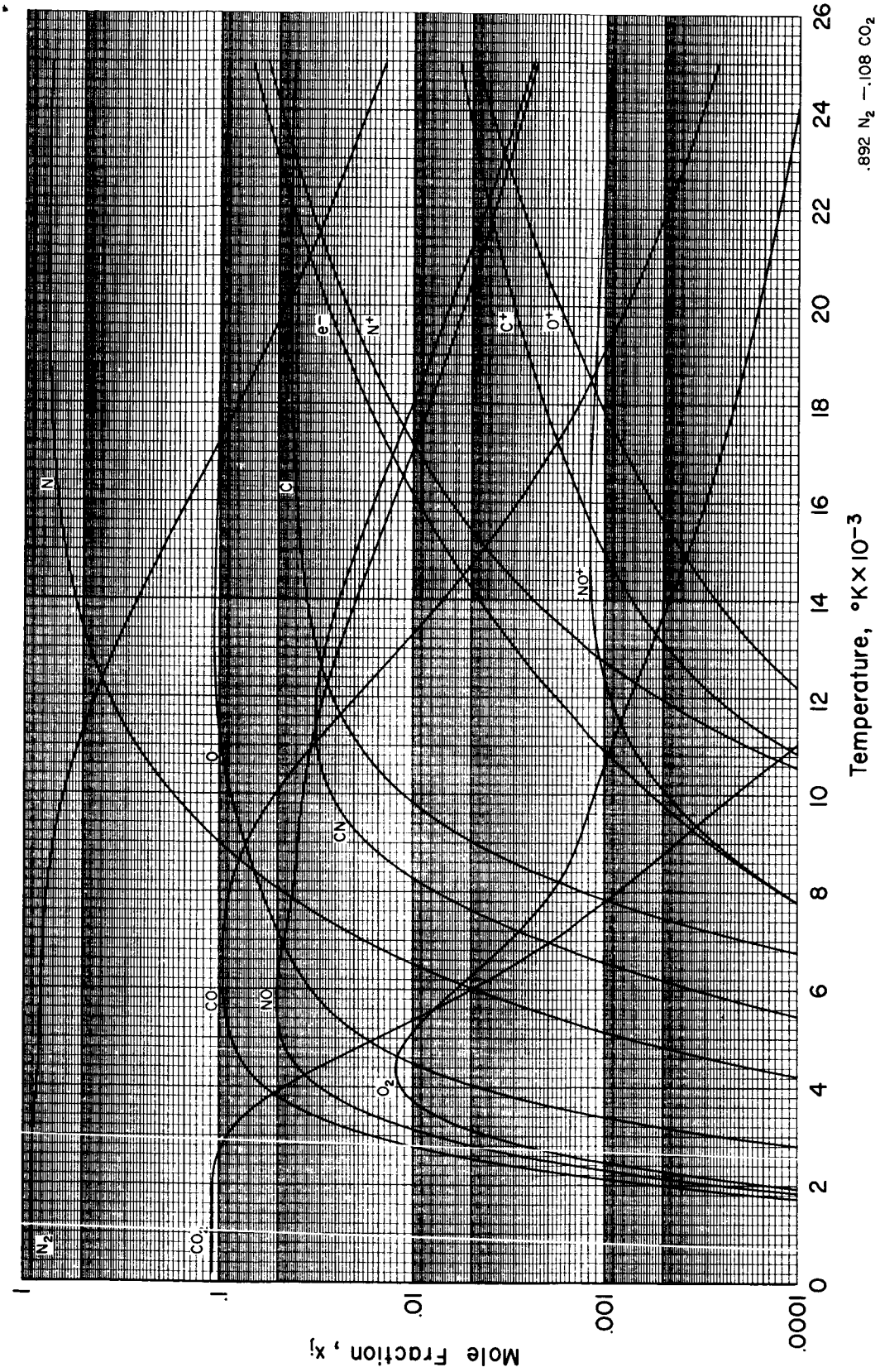
(n) Region 14 - Concluded.

Figure 11. - Concluded.



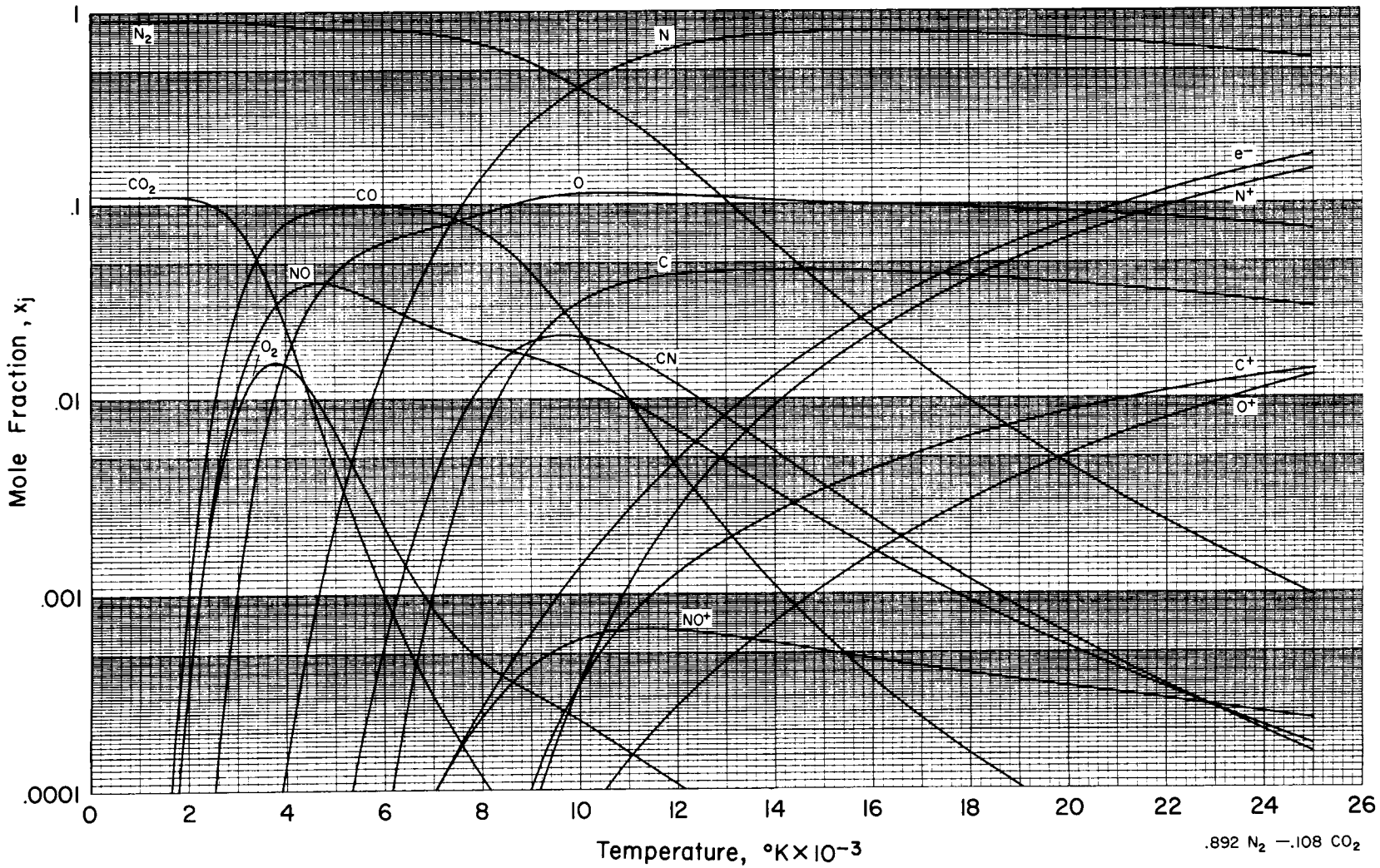
(a) $\rho/\rho_o = 10^3$

Figure 12. - Equilibrium chemical composition.



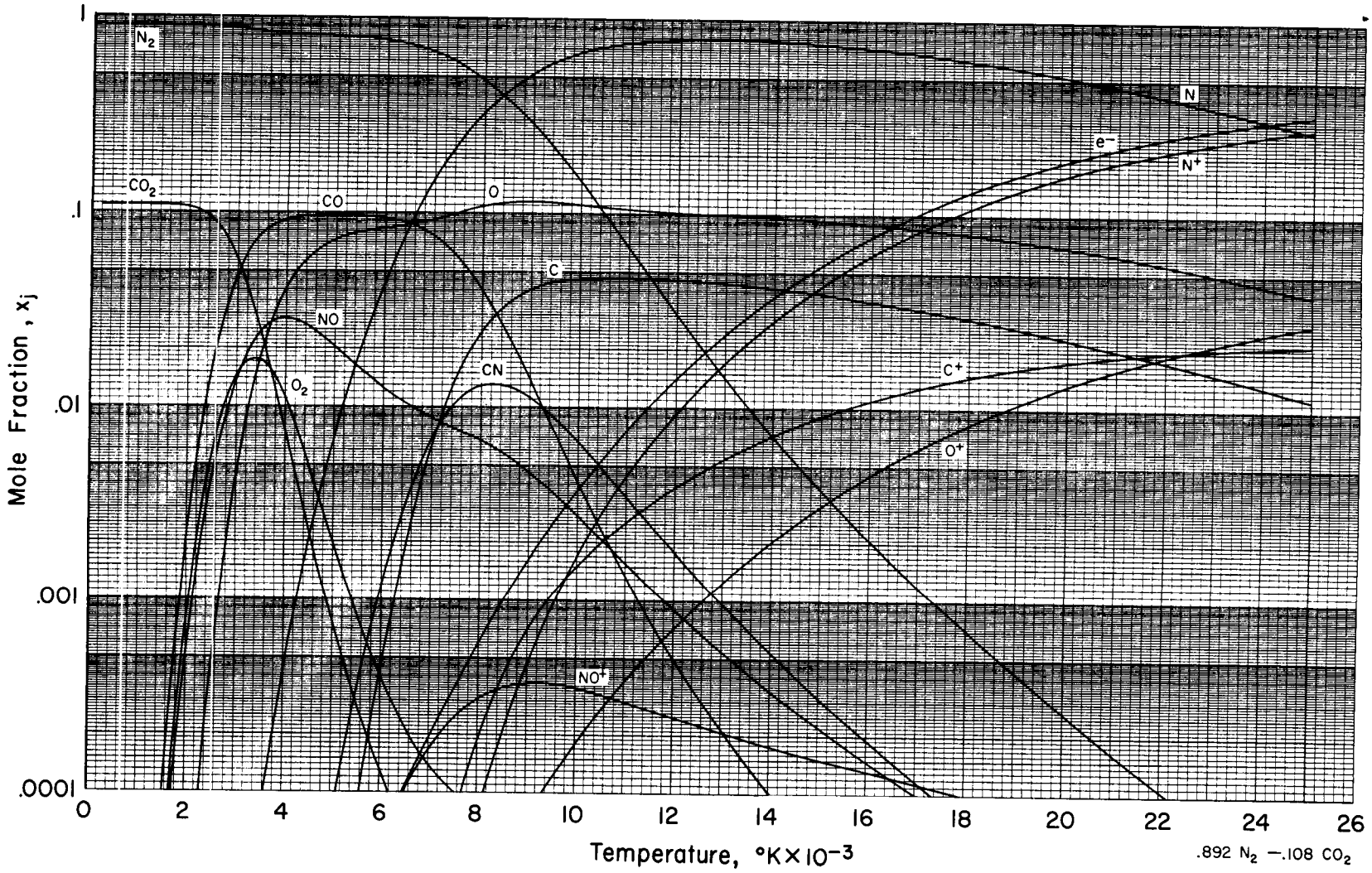
(b) $\rho/\rho_o = 10^2$

Figure 12. - Continued.



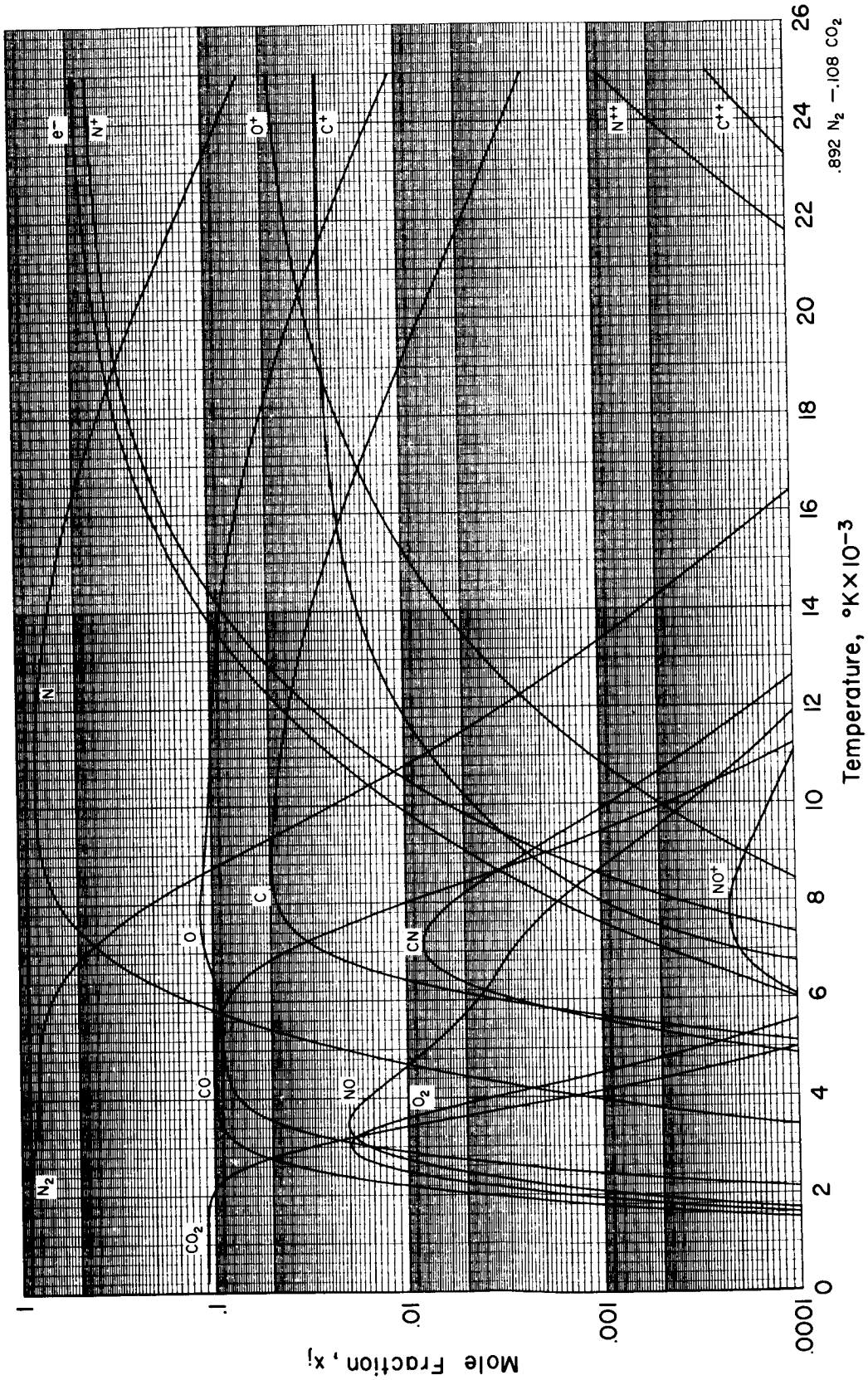
(c) $\rho/\rho_o = 10$

Figure 12. - Continued.



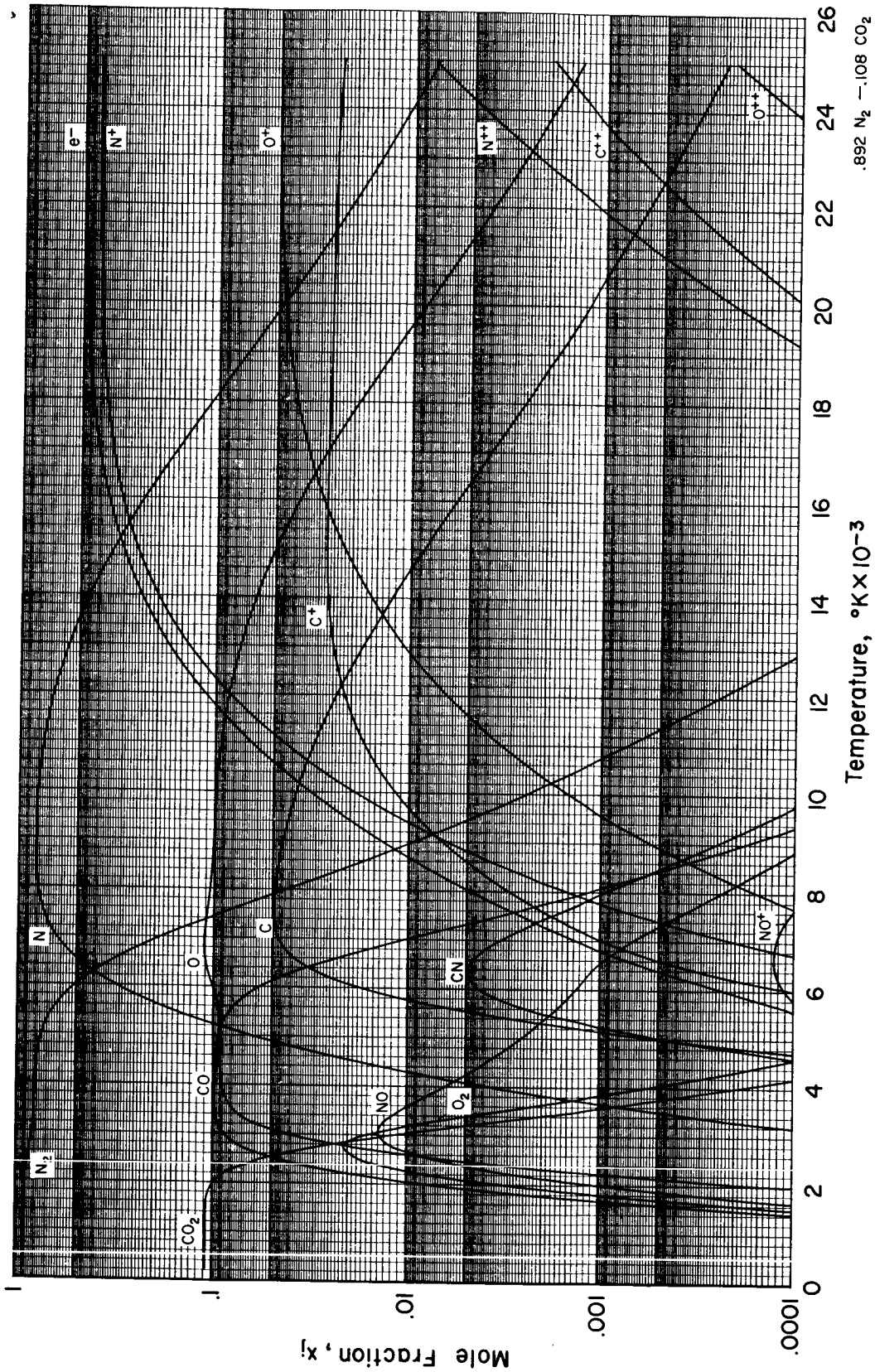
(d) $\rho/\rho_0 = 1$

Figure 12. - Continued.



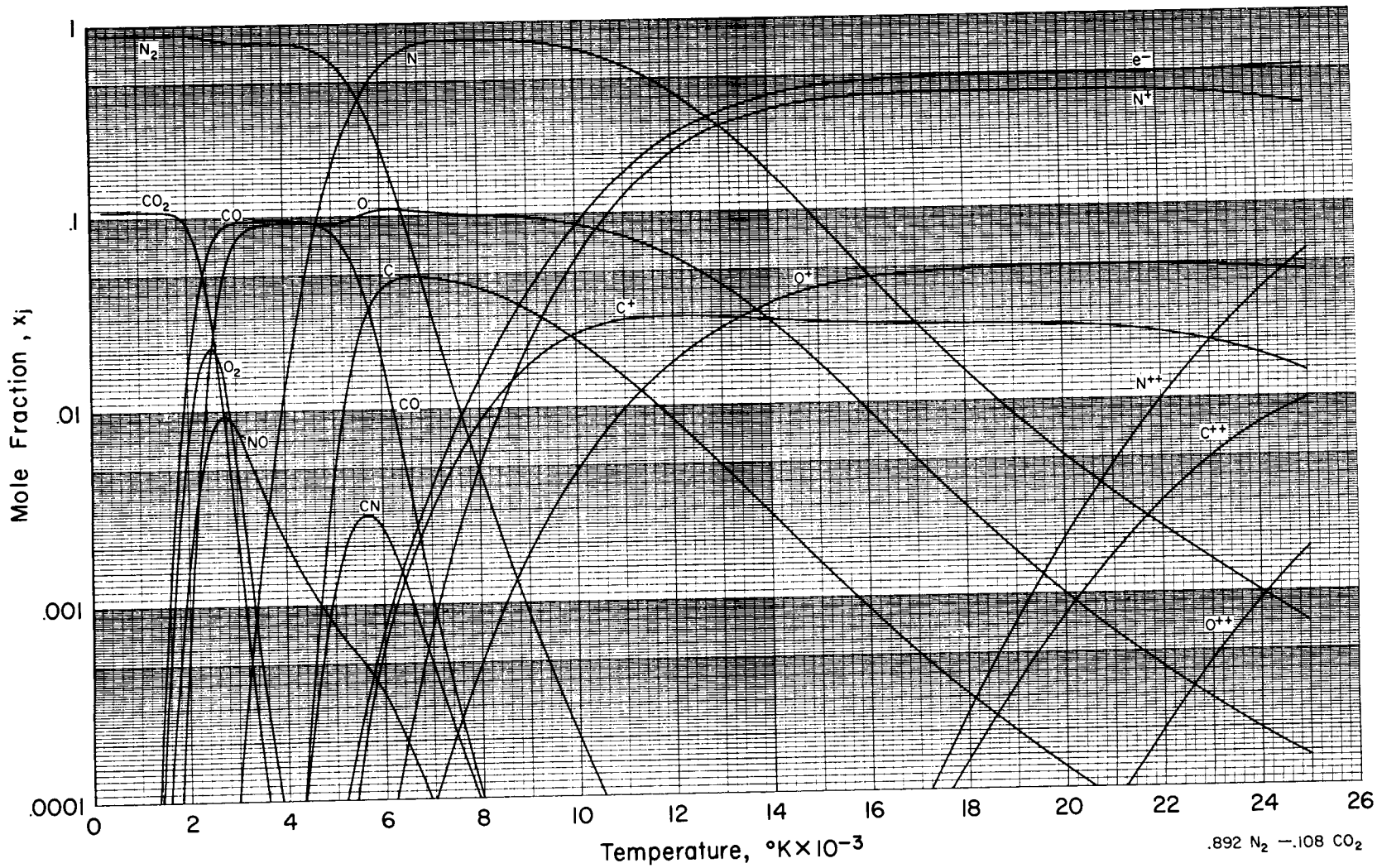
(e) $\rho/\rho_o = 10^{-1}$

Figure 12. - Continued.



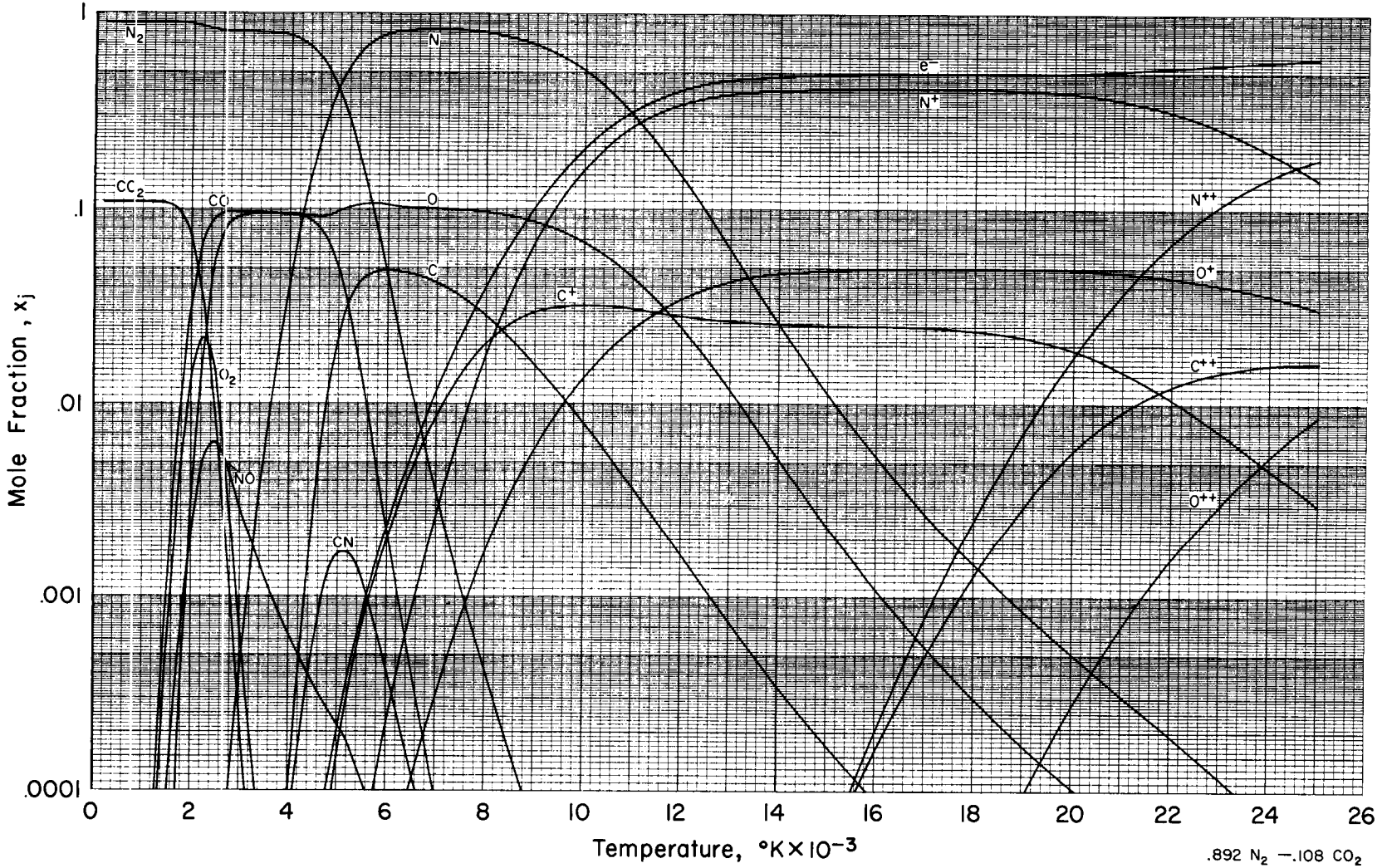
(f) $\rho/\rho_0 = 10^{-2}$

Figure 12. - Continued.



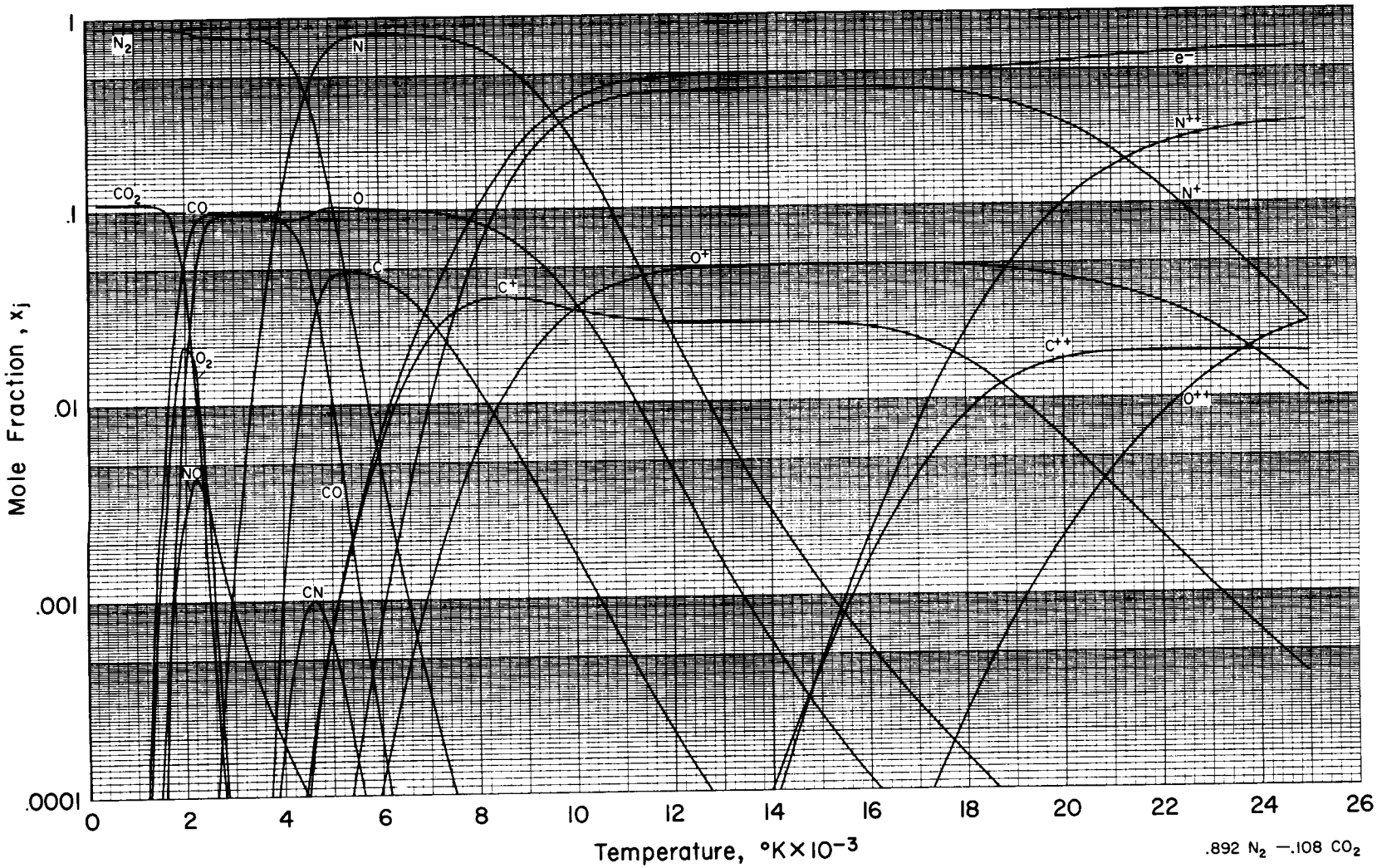
(g) $\rho/\rho_o = 10^{-3}$

Figure 12. - Continued.



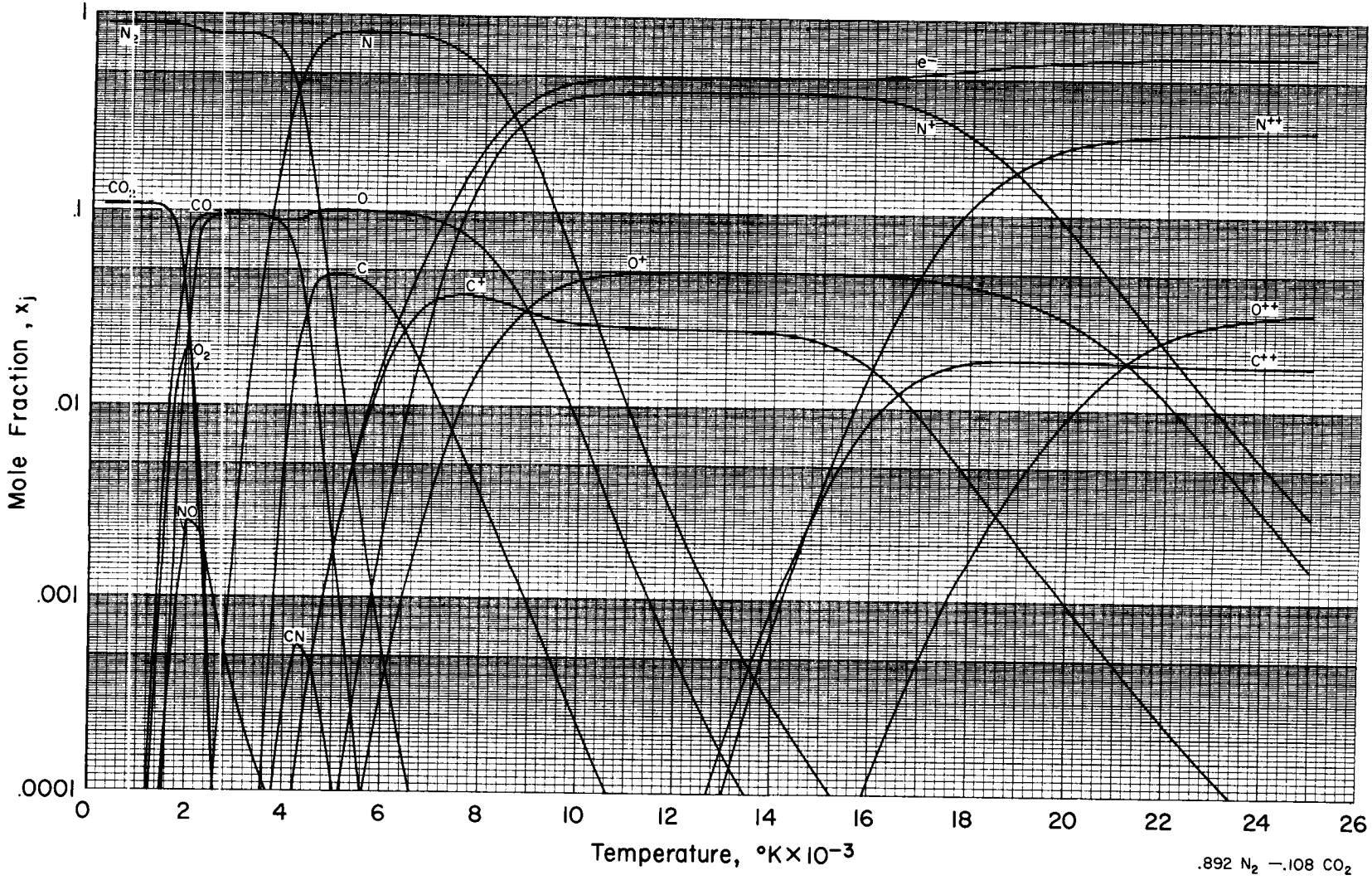
(h) $\rho/\rho_o = 10^{-4}$

Figure 12. - Continued.



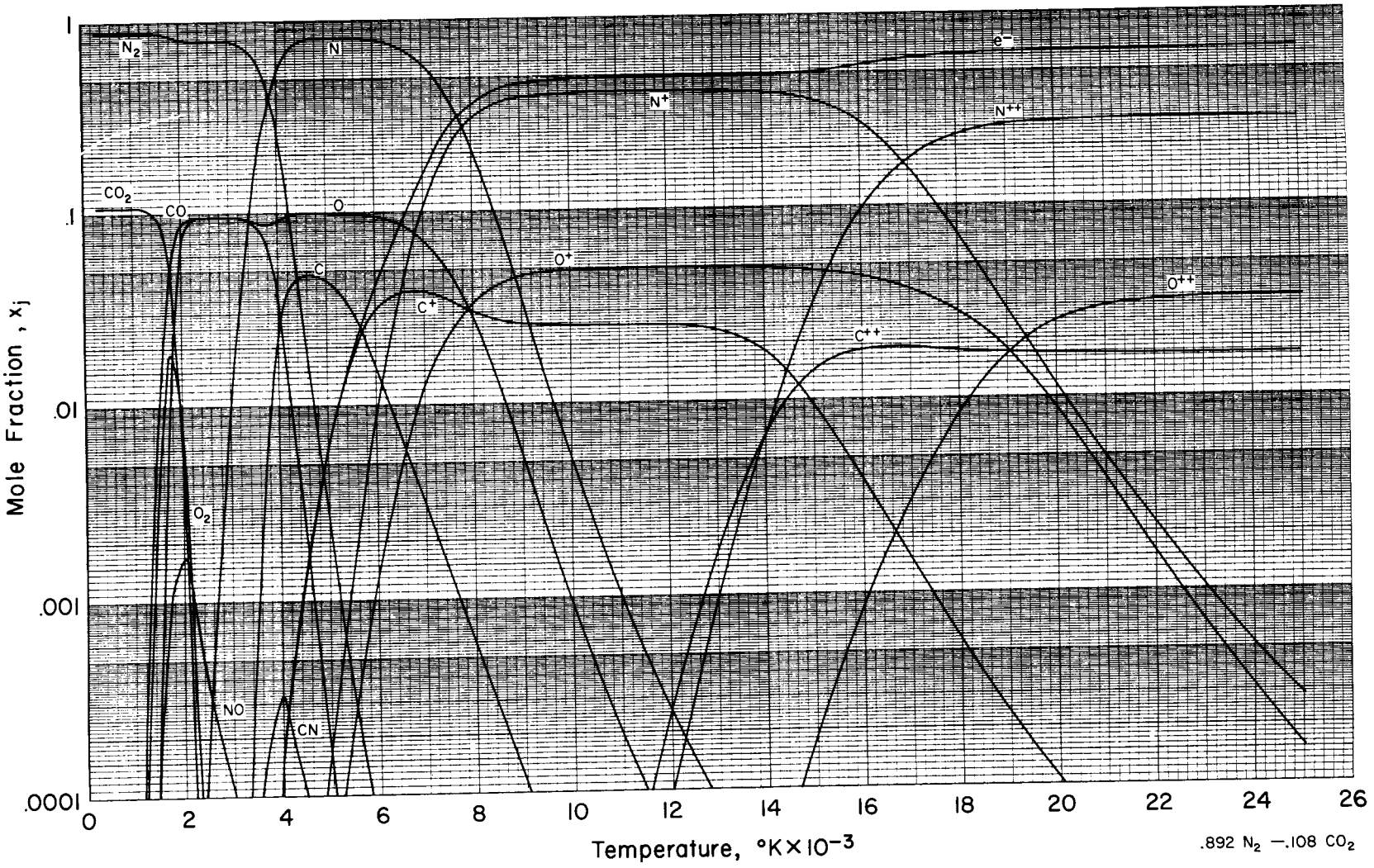
(i) $\rho/\rho_0 = 10^{-5}$

Figure 12. - Continued.



(j) $\rho/\rho_o = 10^{-6}$

Figure 12. - Continued.



(k) $\rho/\rho_0 = 10^{-7}$

Figure 12. - Concluded.

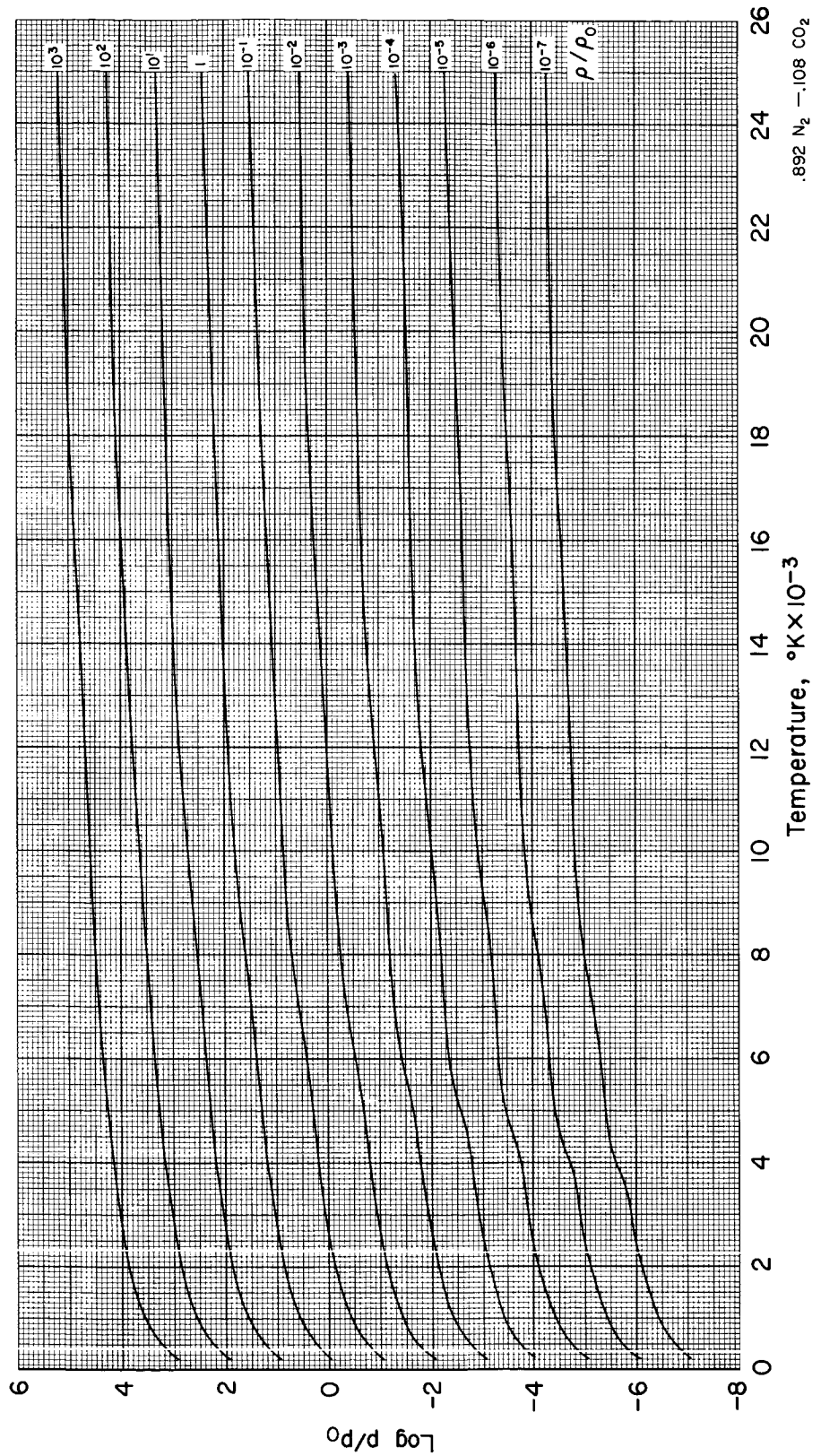


Figure 13. - Pressure as a function of temperature.

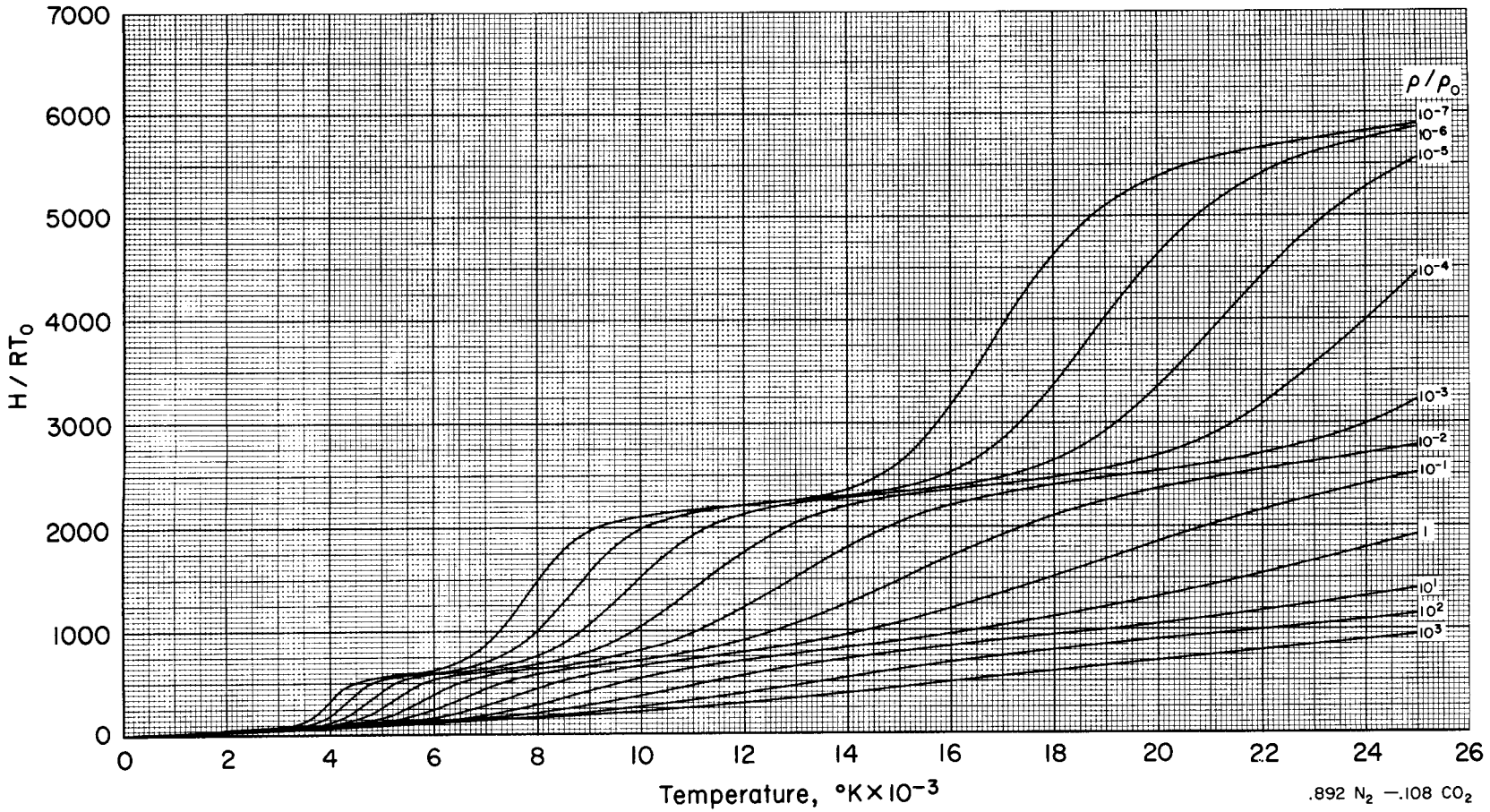


Figure 14. - Enthalpy as a function of temperature.

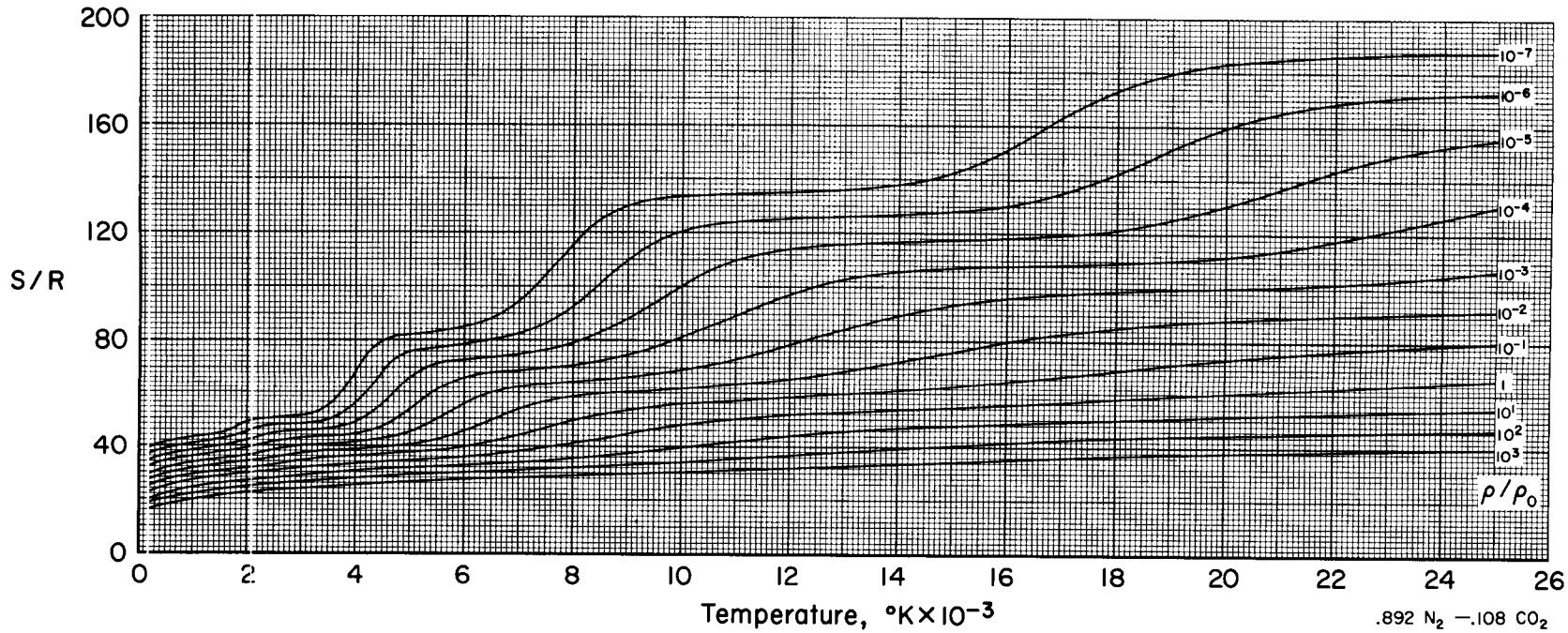


Figure 15. - Entropy as a function of temperature.

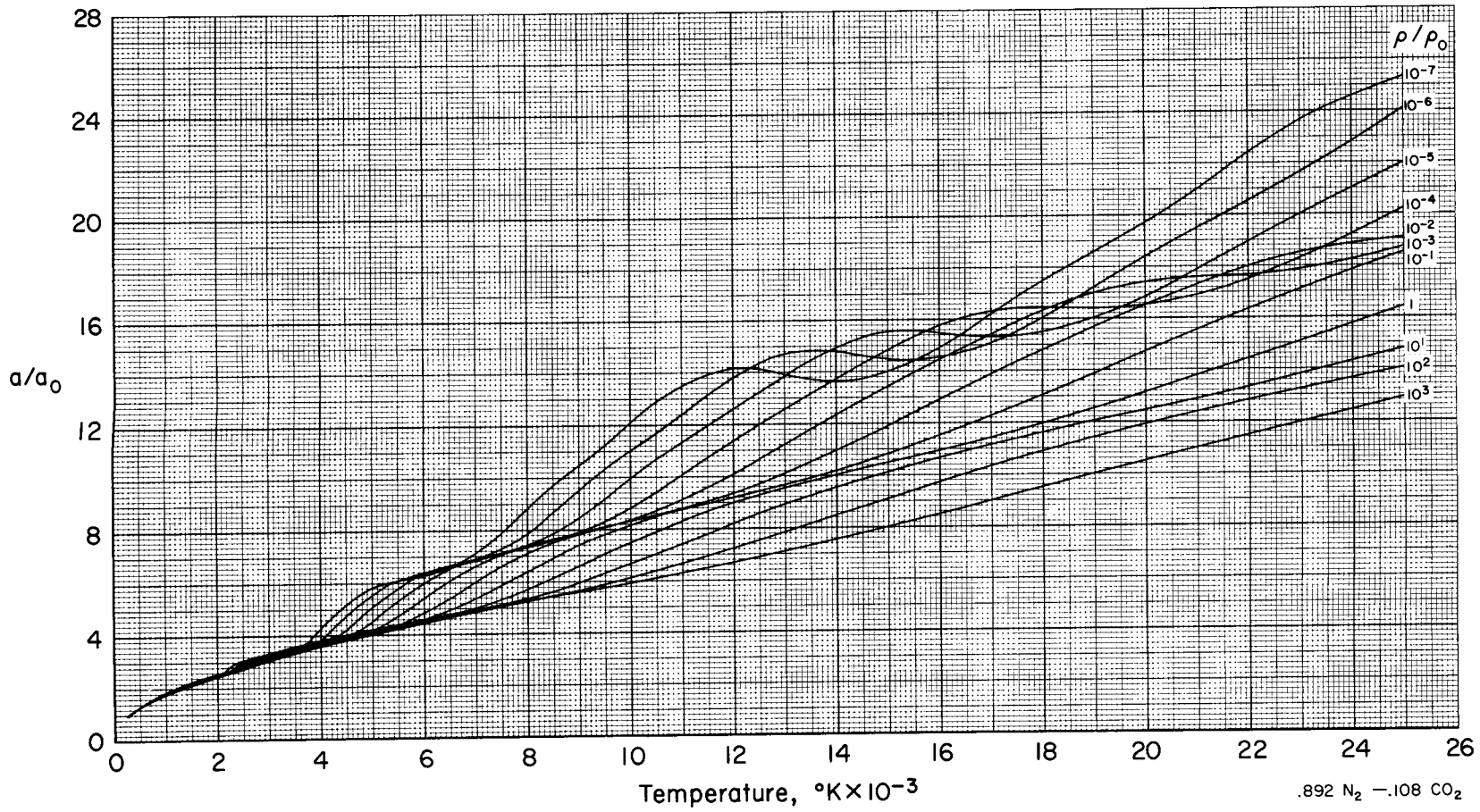


Figure 16. - Sound speed as a function of temperature.

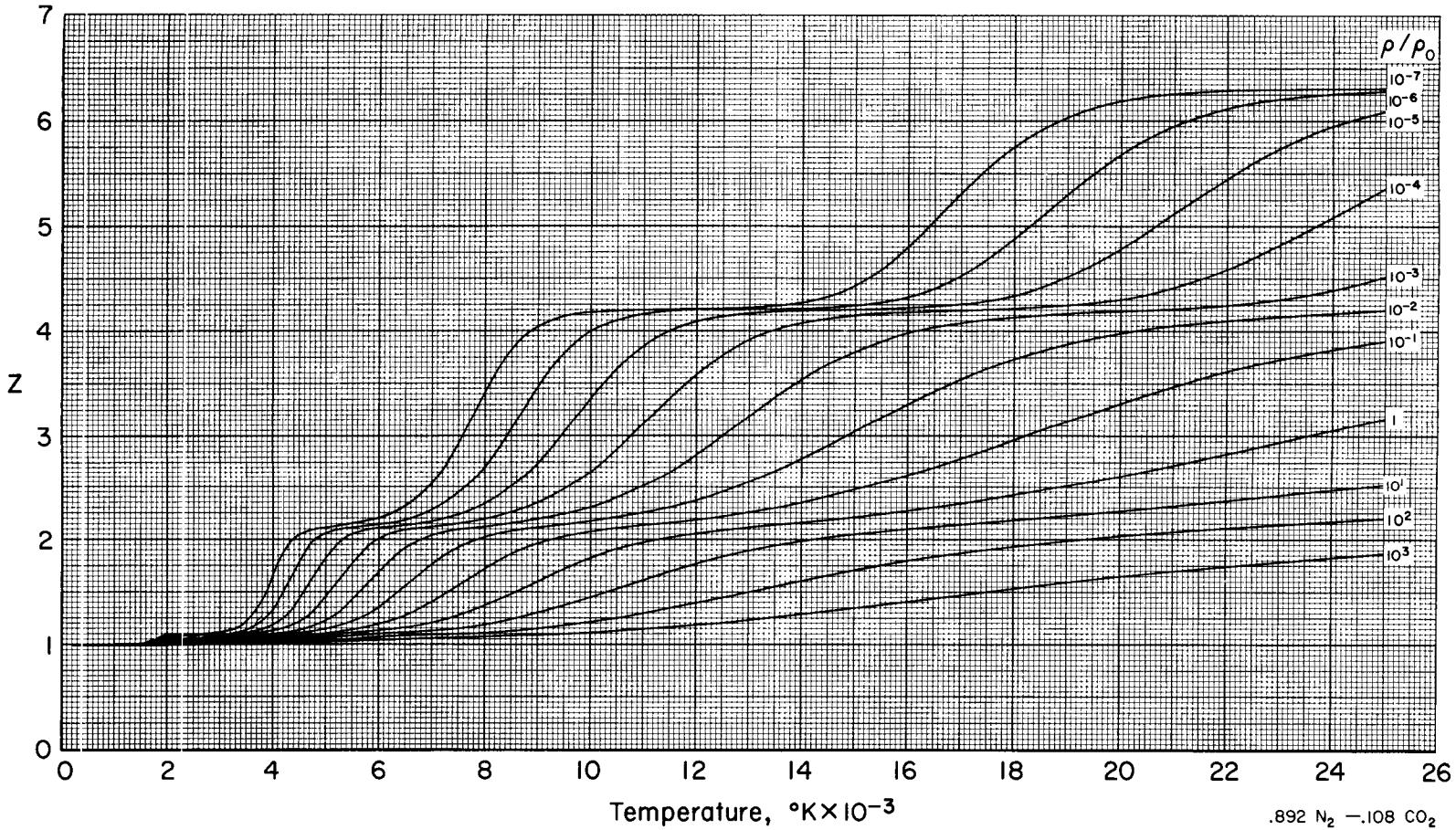
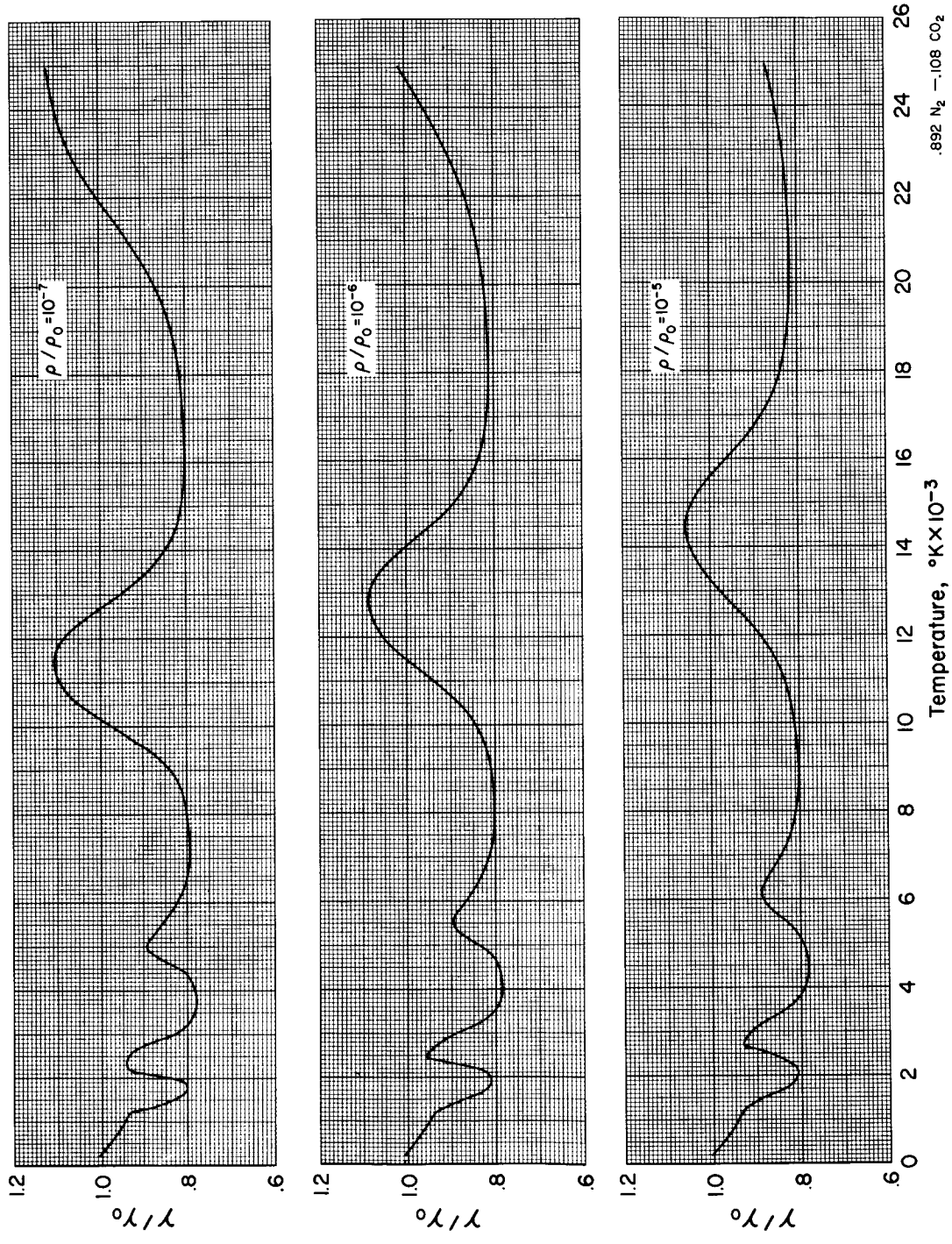
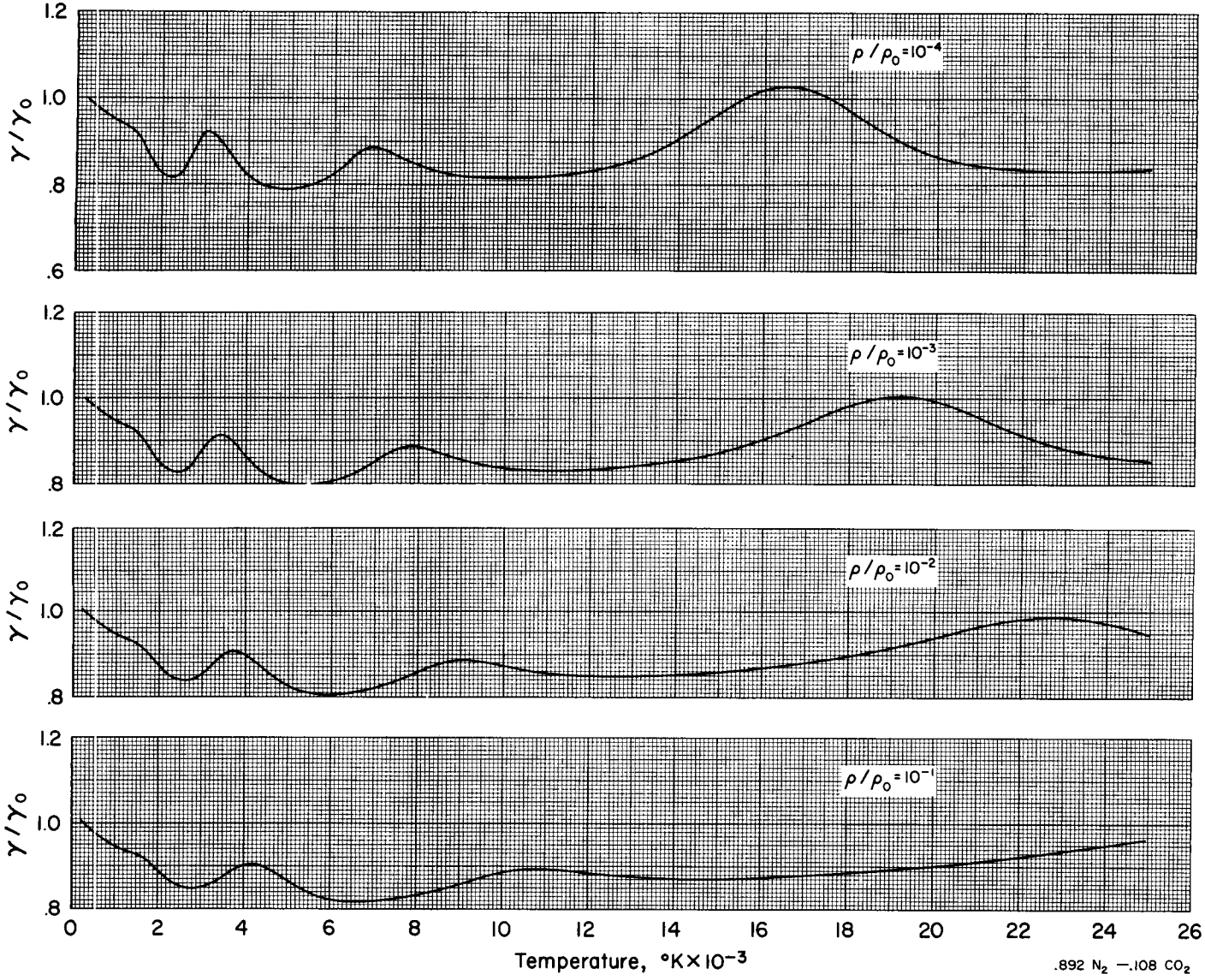


Figure 17. - Compressibility factor as a function of temperature.



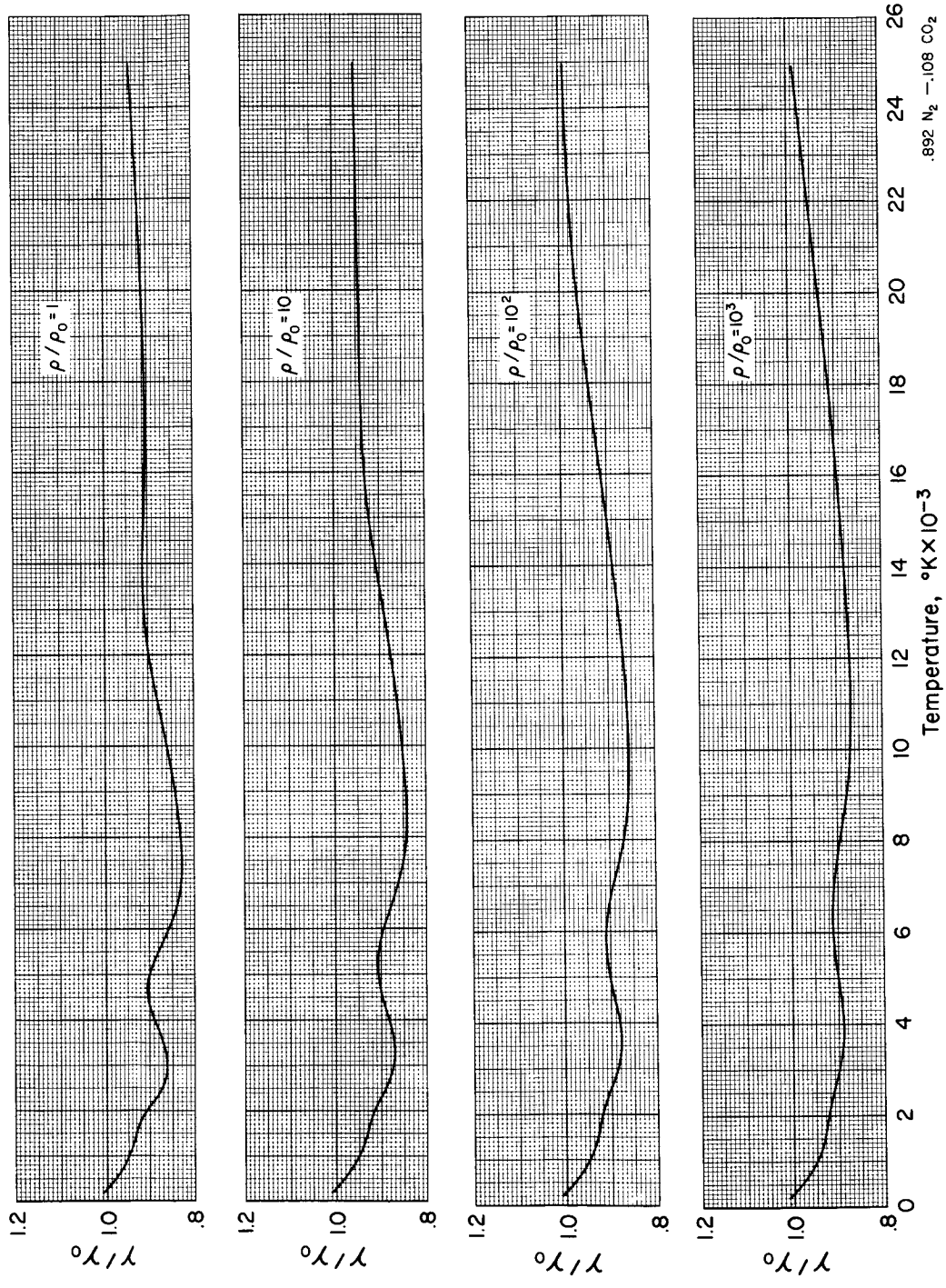
(a) $\rho/\rho_0 = 10^{-7}$ to 10^{-5}; $\gamma_0 = 1.384$

Figure 18. - Isentropic exponent as a function of temperature.



(b) $\rho/\rho_0 = 10^{-4}$ to 10^{-1}; $\gamma_0 = 1.384$

Figure 18. - Continued.



(c) $\rho/\rho_0 = 1$ to 10^3; $\gamma_0 = 1.384$

Figure 18.–Concluded.

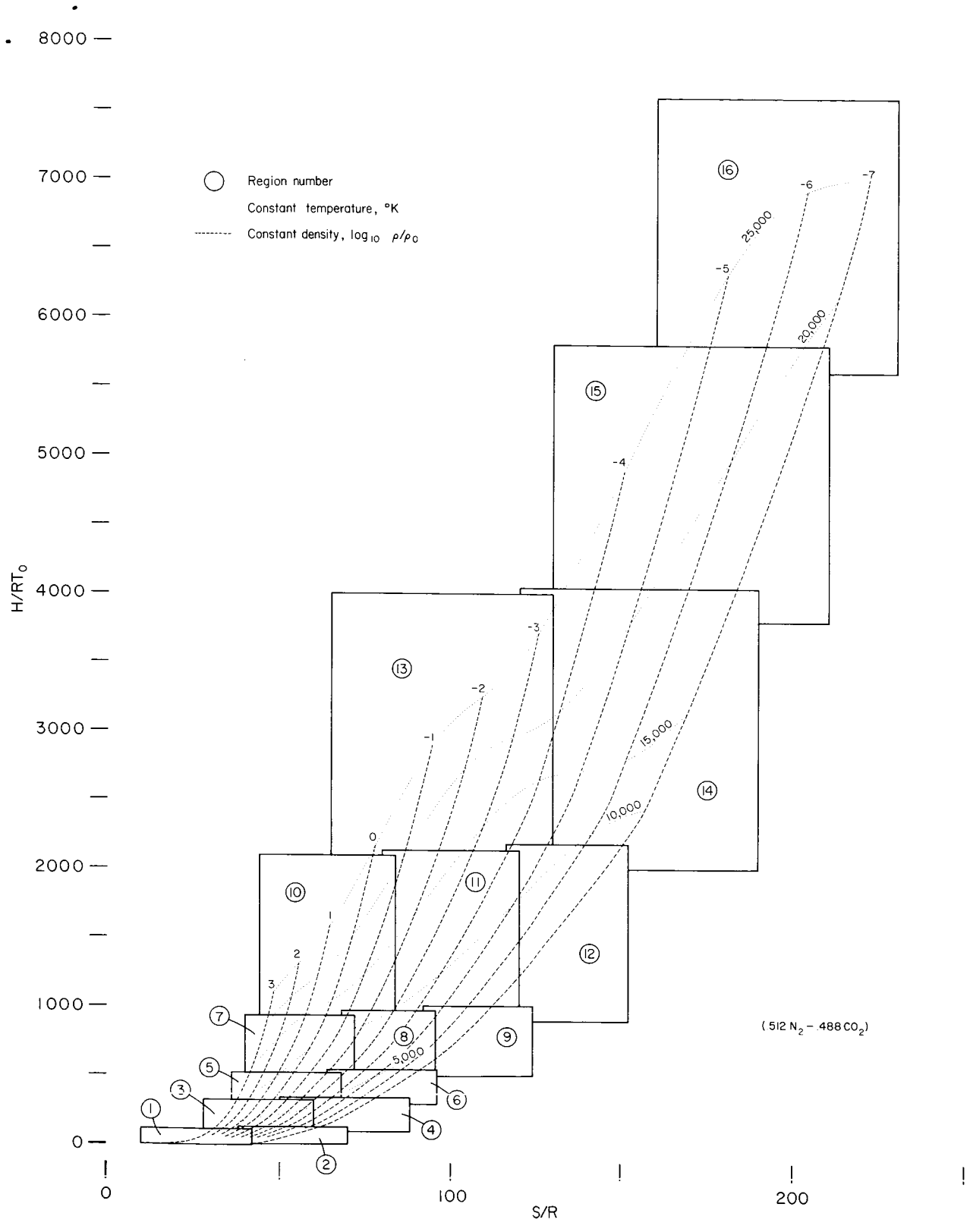
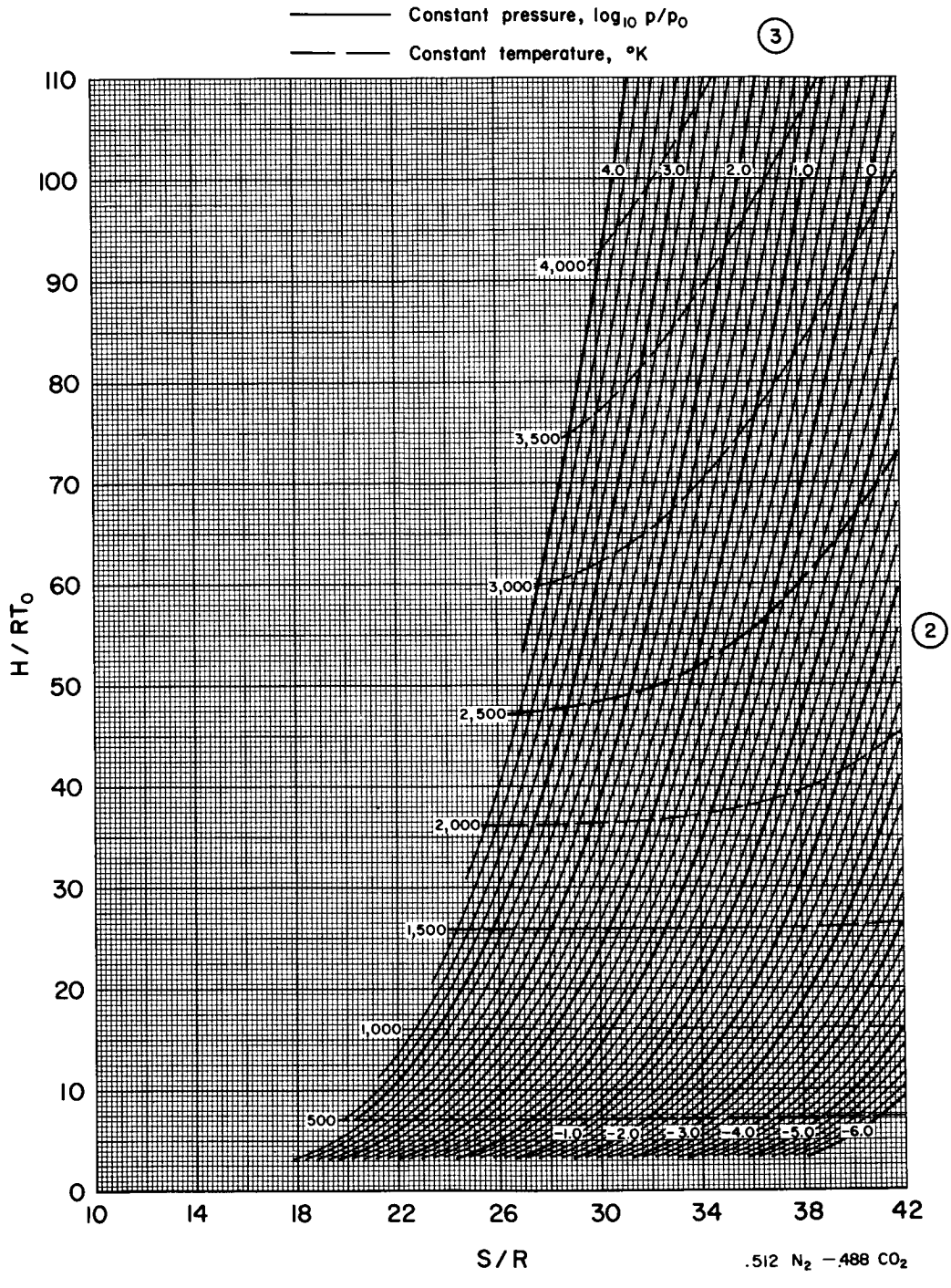
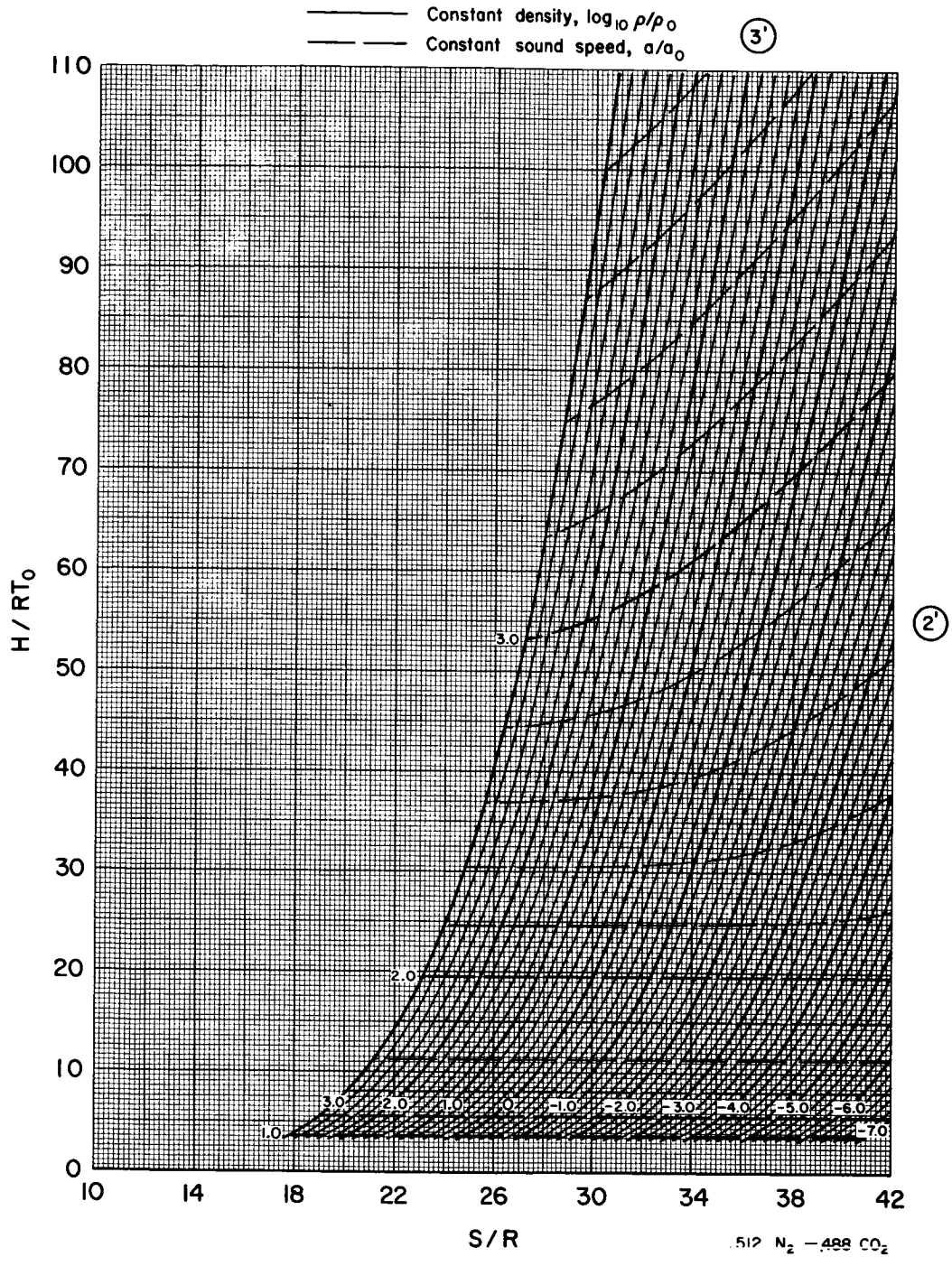


Figure 19. - Key to presentation of thermodynamic data.



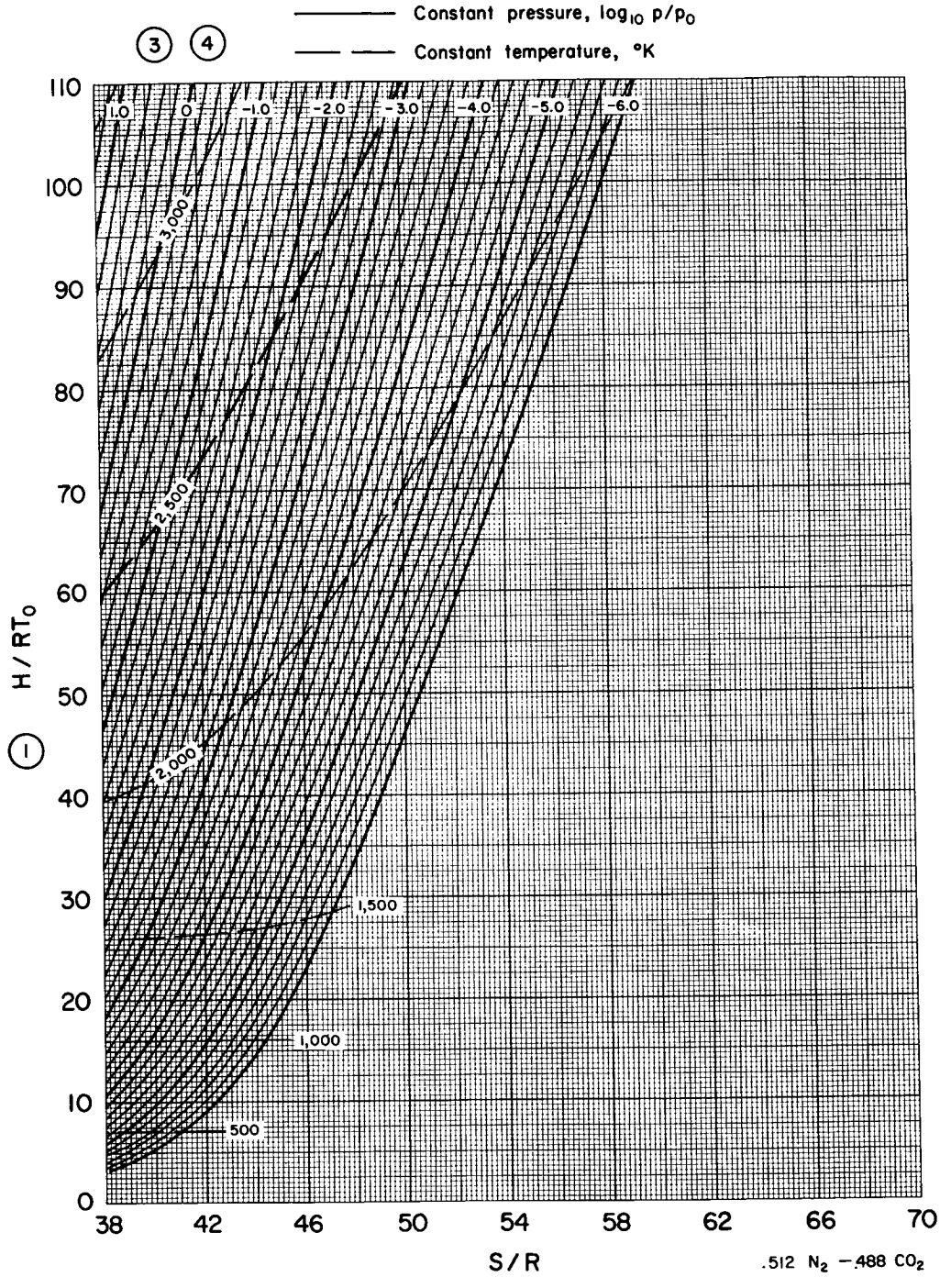
(a) Region 1.

Figure 20. - Thermodynamic data.



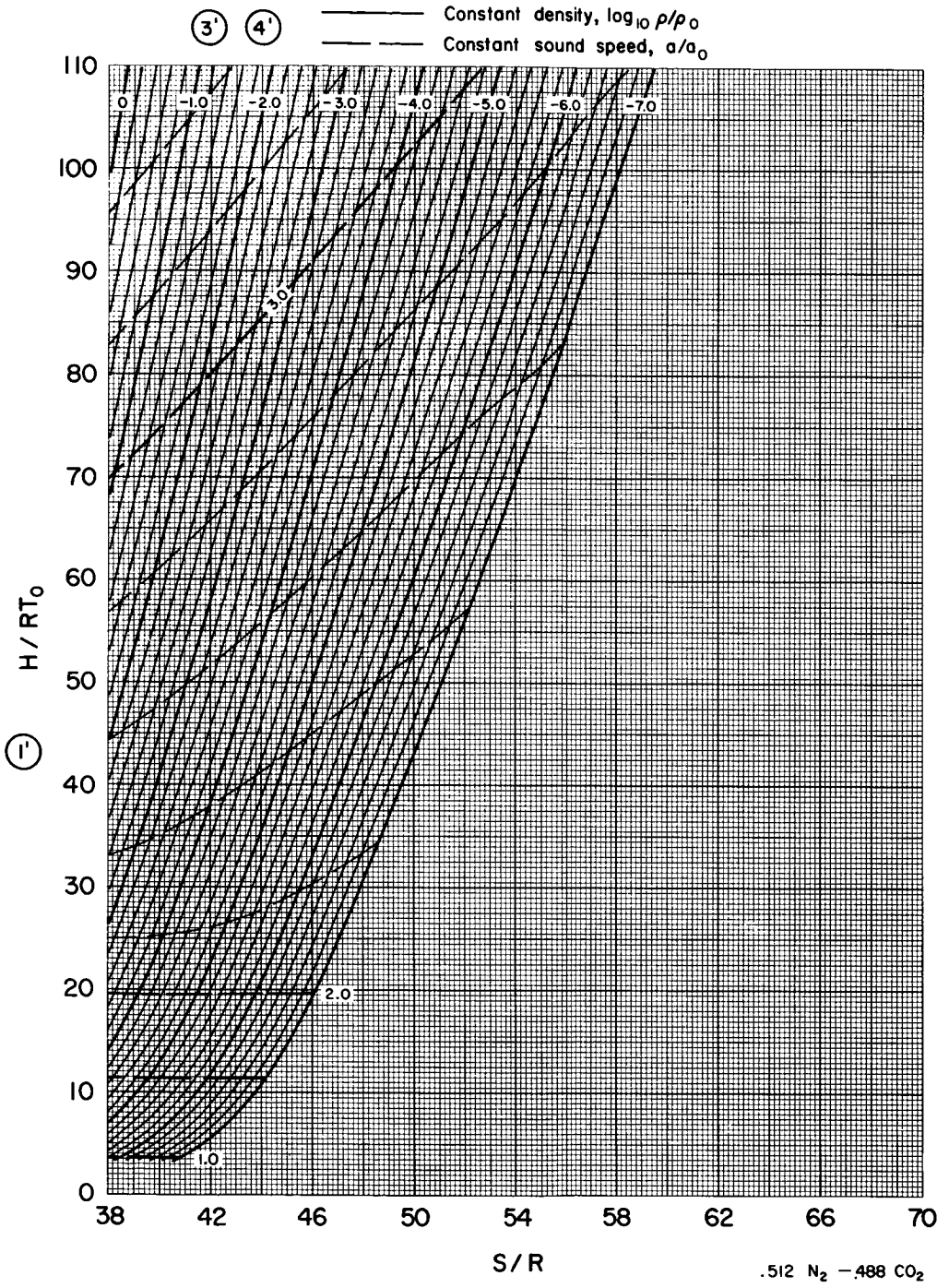
(a) Region 1 - Concluded.

Figure 20. - Continued.



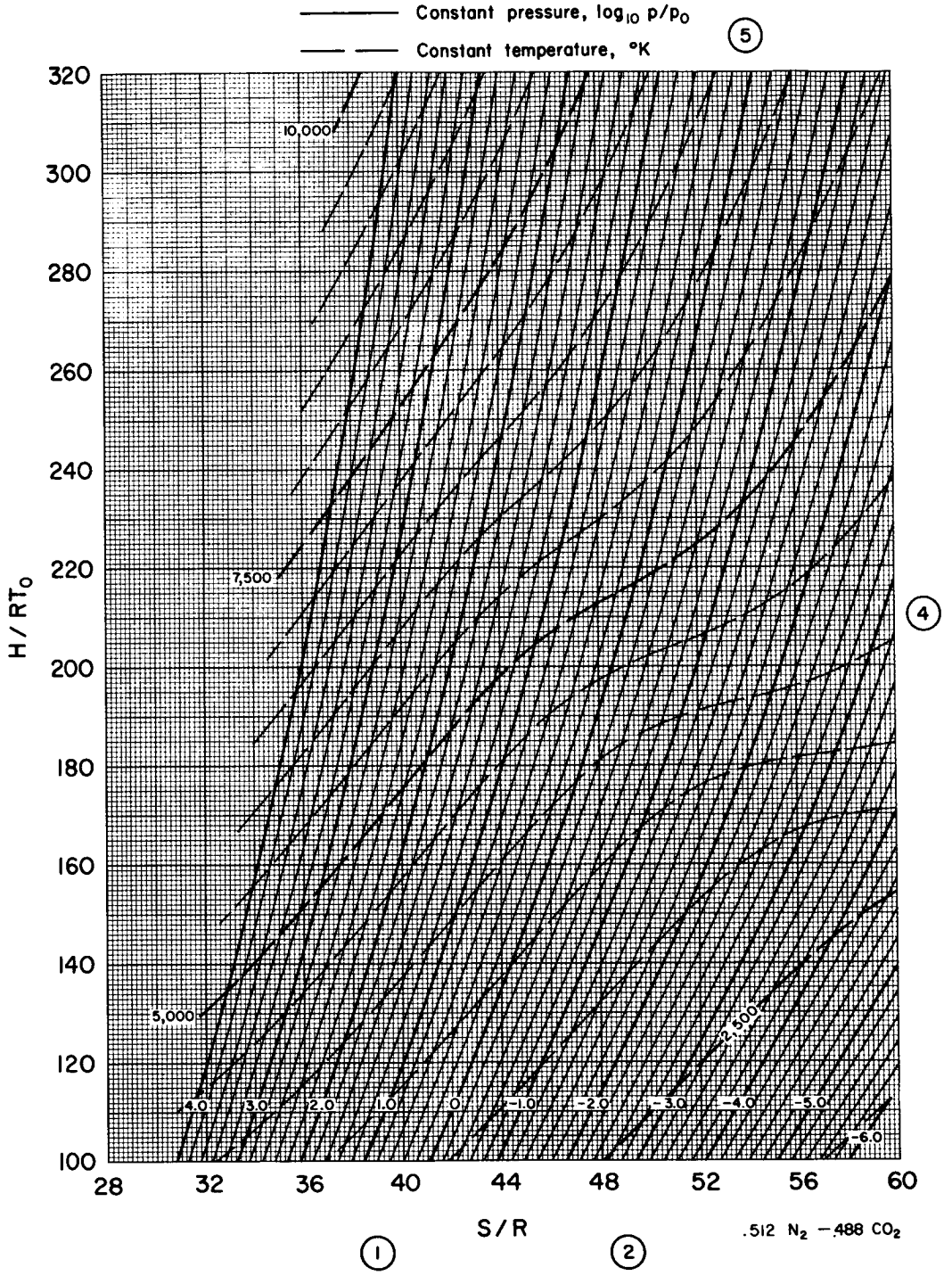
(b) Region 2.

Figure 20. - Continued.



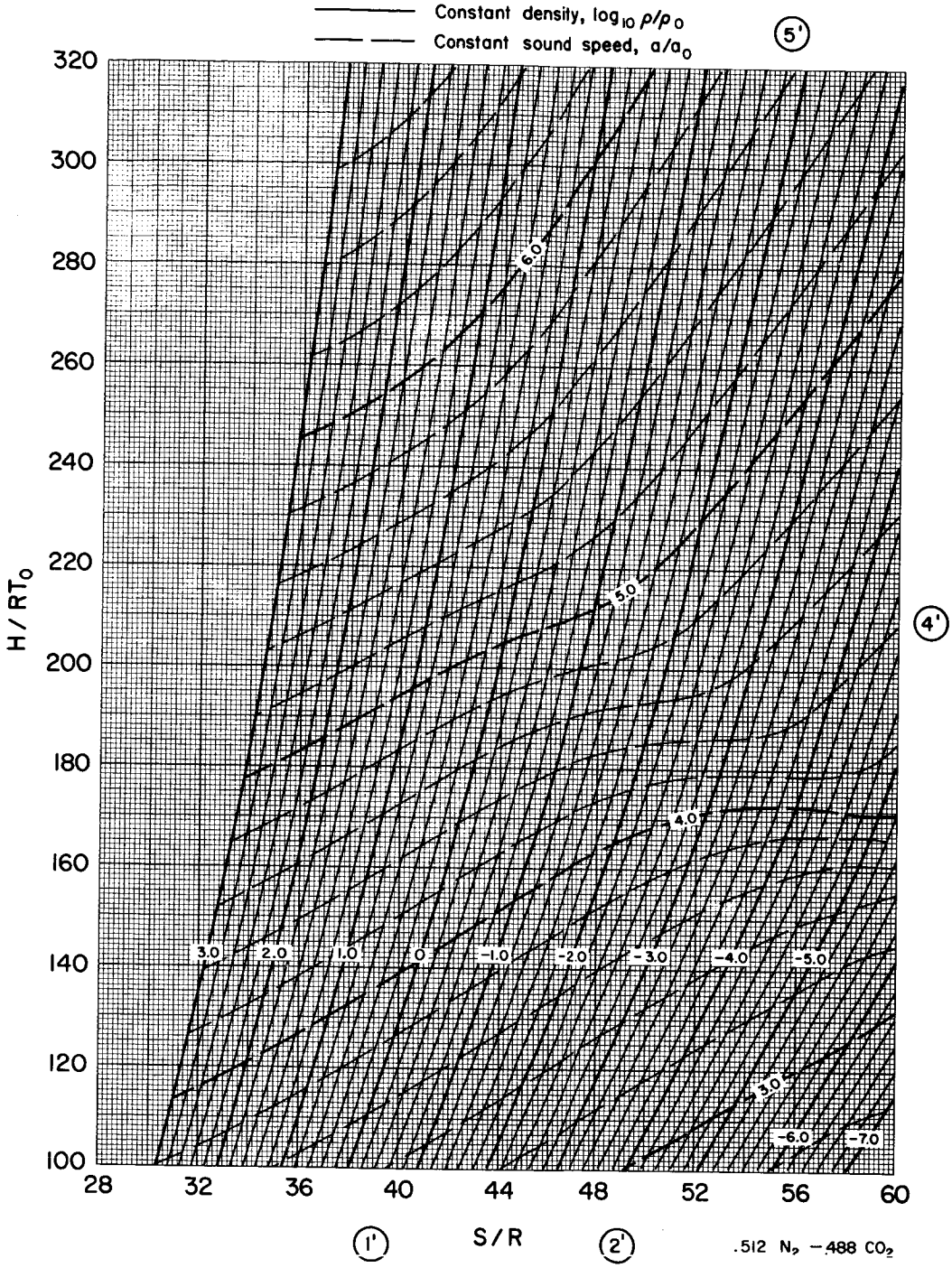
(b) Region 2 - Concluded.

Figure 20. - Continued.



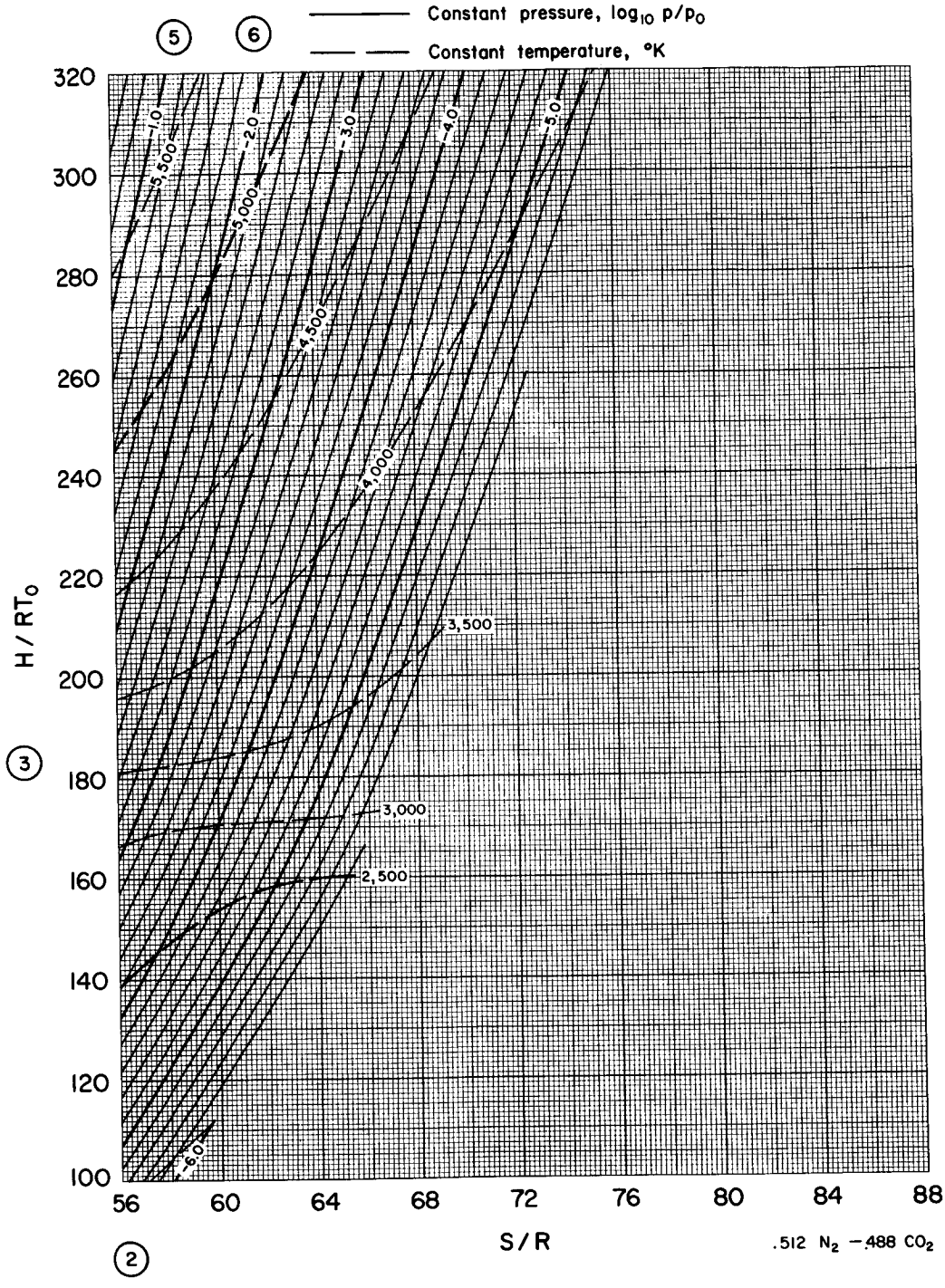
(c) Region 3.

Figure 20. - Continued.



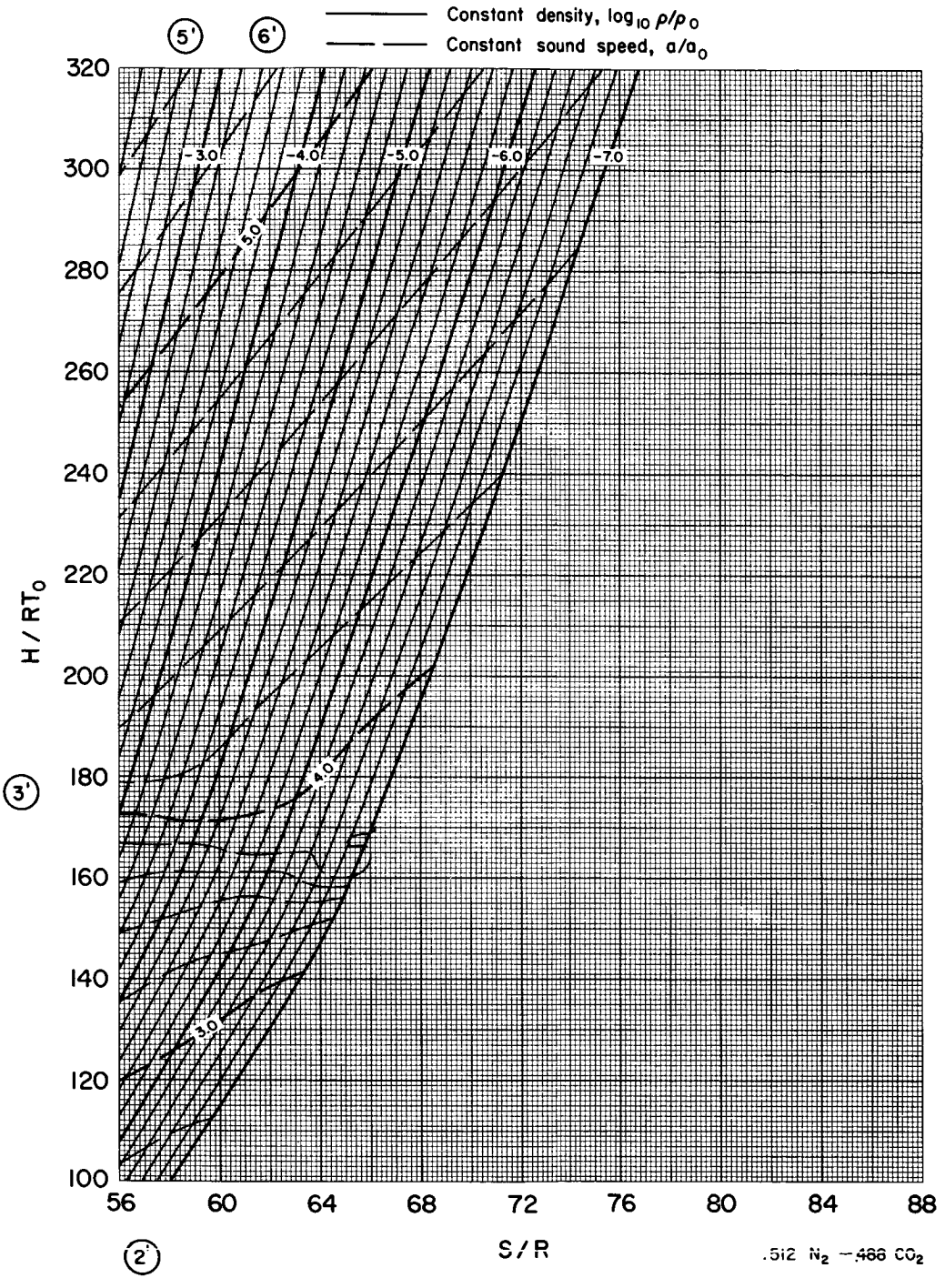
(c) Region 3 - Concluded.

Figure 20. - Continued.



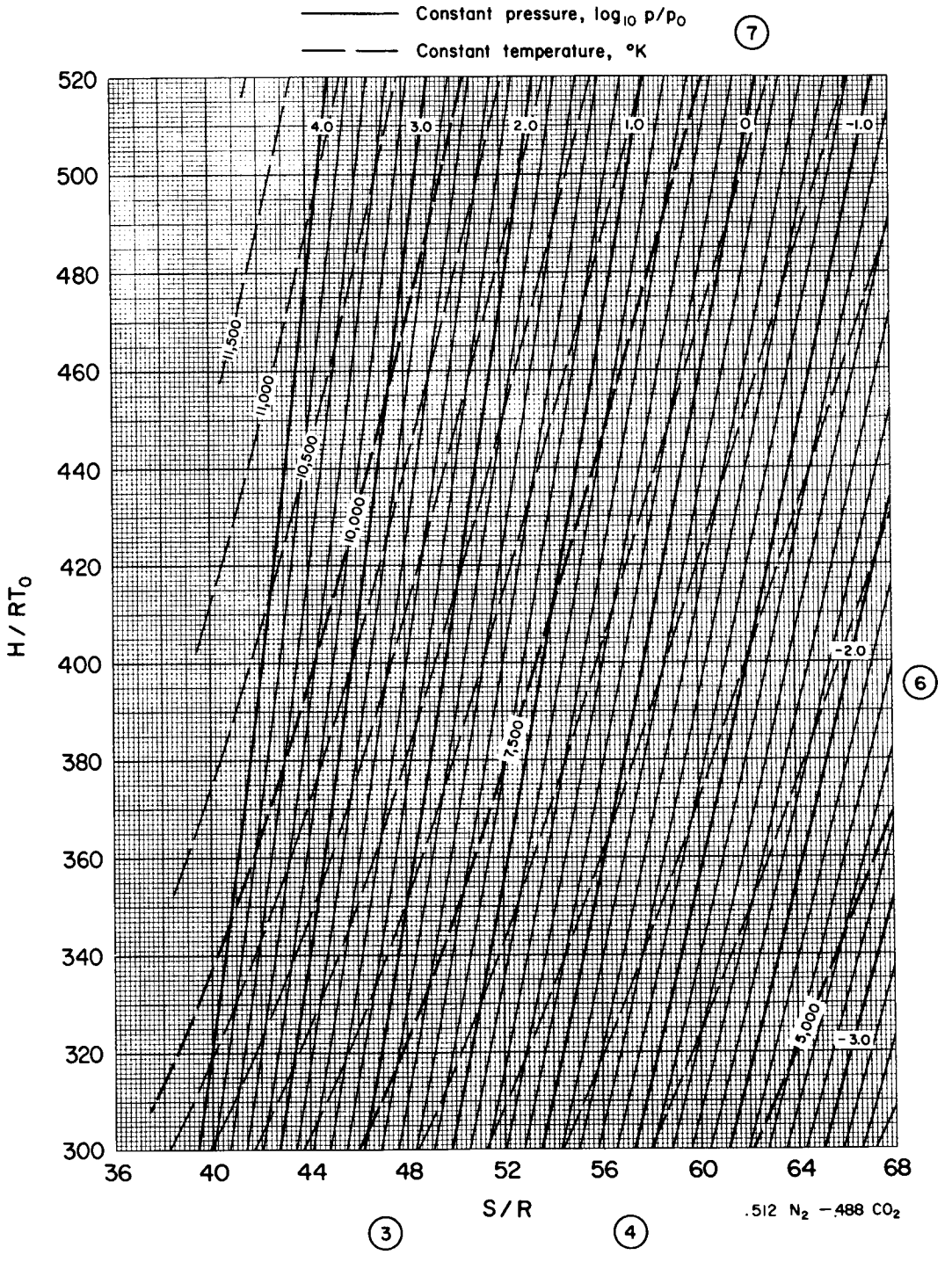
(d) Region 4.

Figure 20. - Continued.



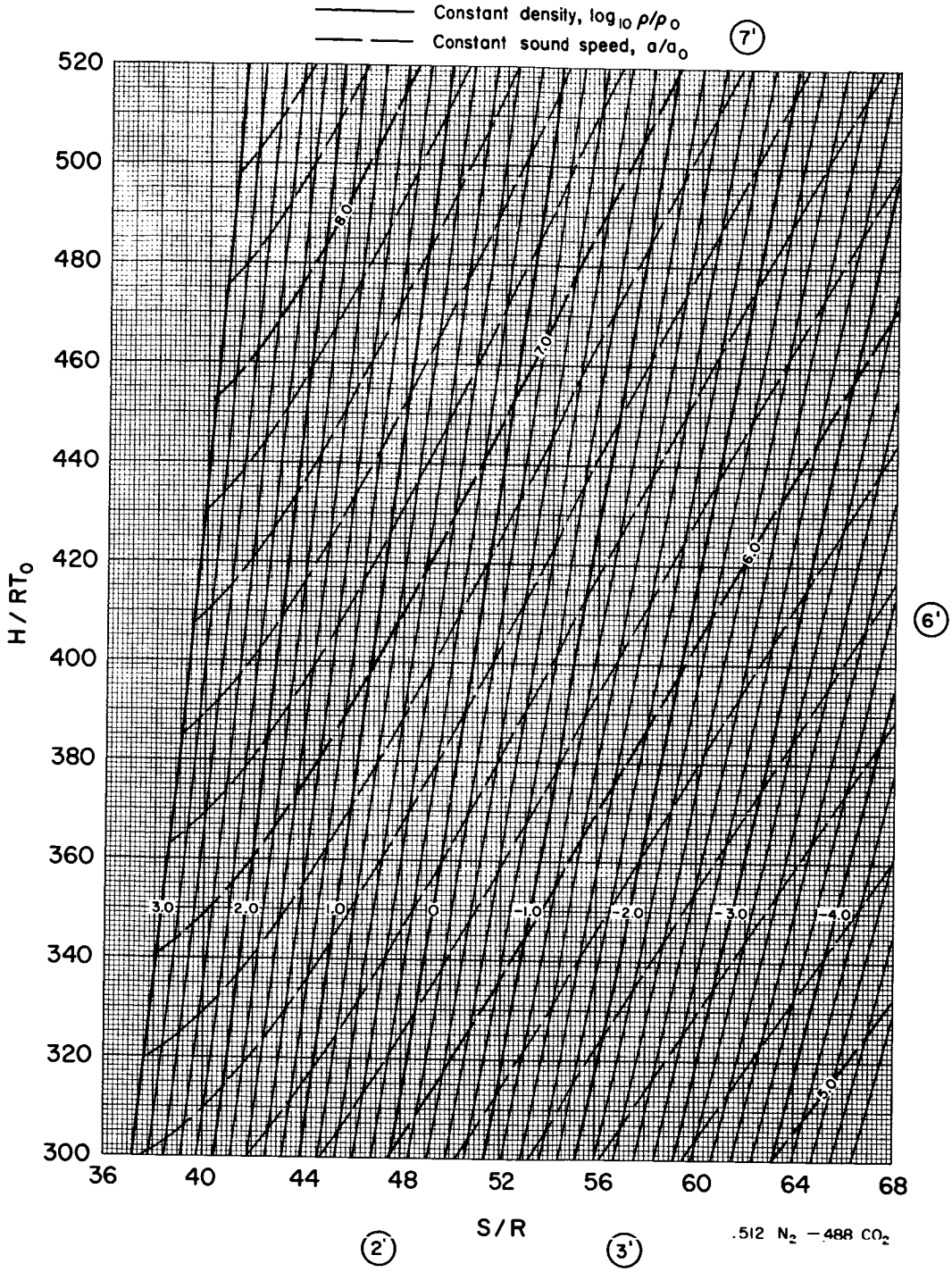
(d) Region 4 - Concluded.

Figure 20. - Continued.



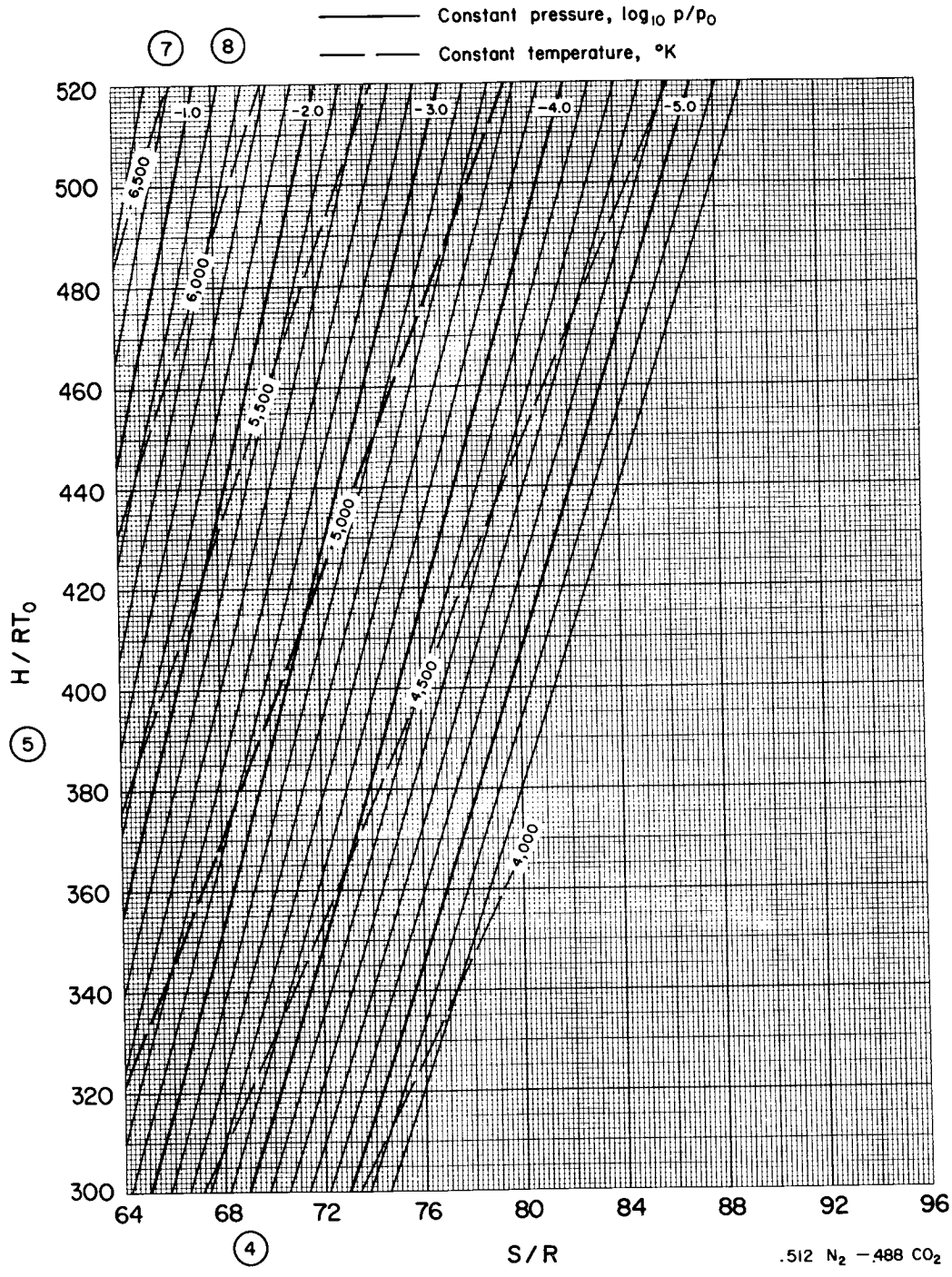
(e) Region 5.

Figure 20. - Continued.



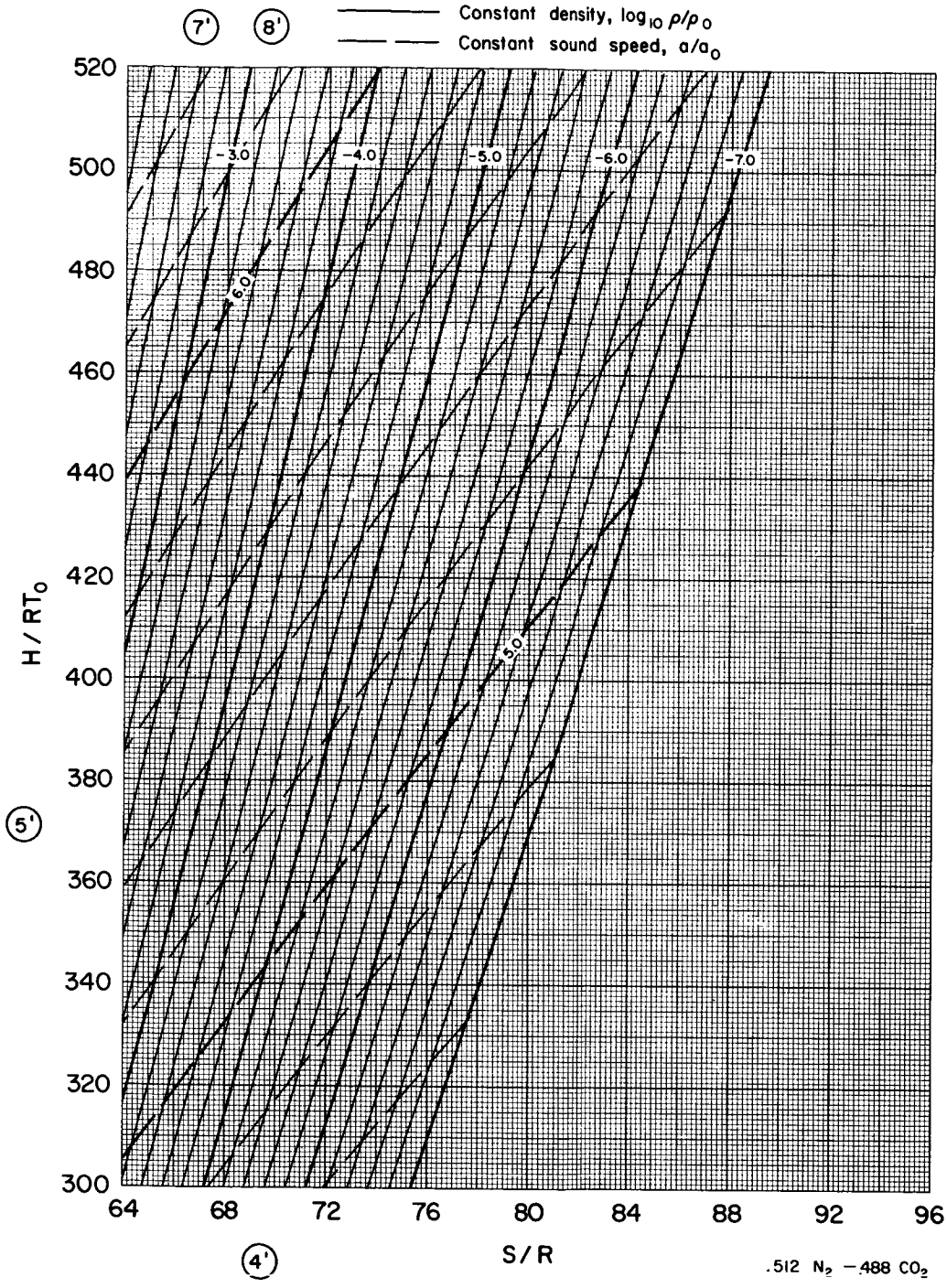
(e) Region 5 - Concluded.

Figure 20. - Continued.



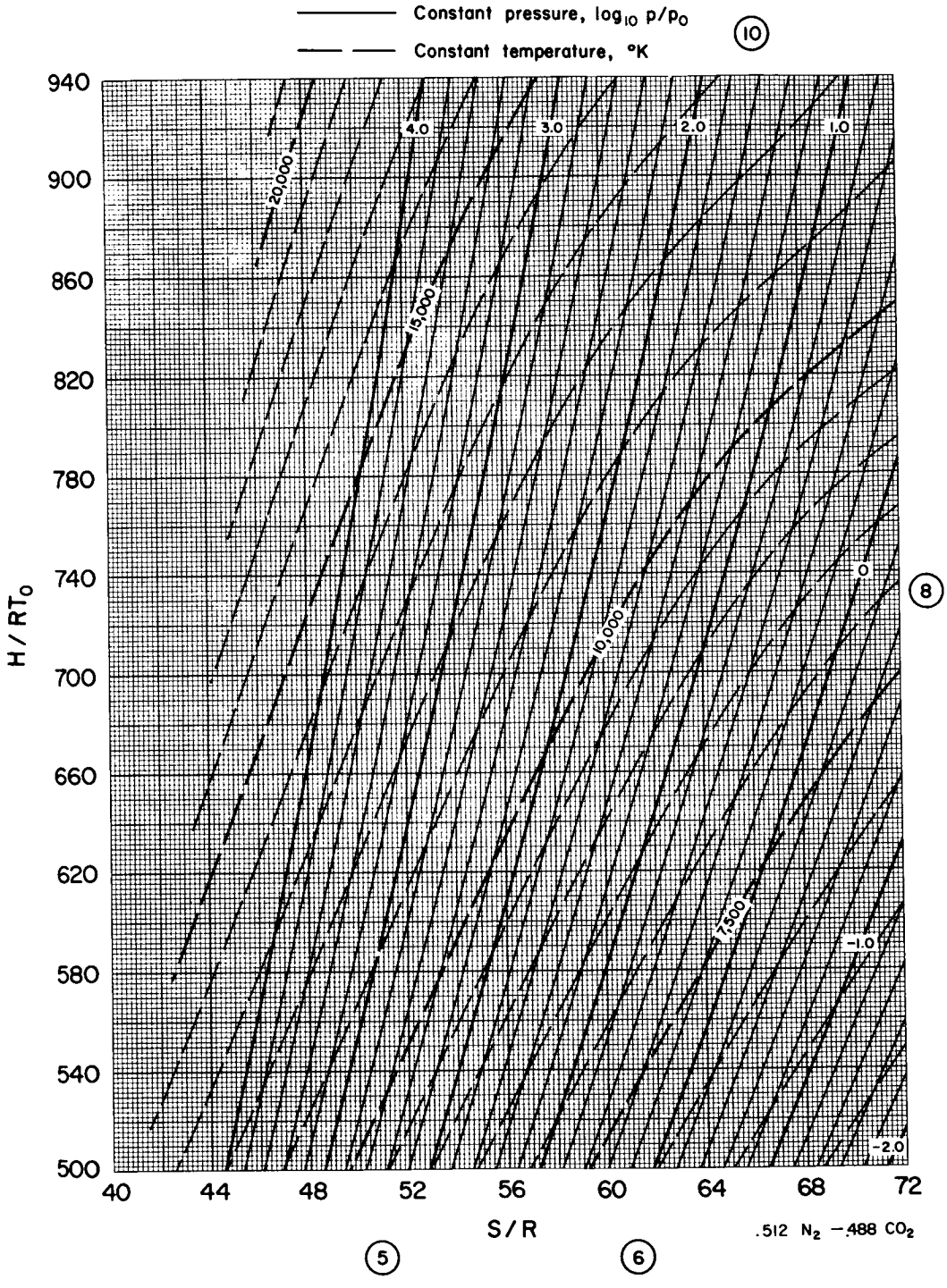
(f) Region 6.

Figure 20. - Continued.



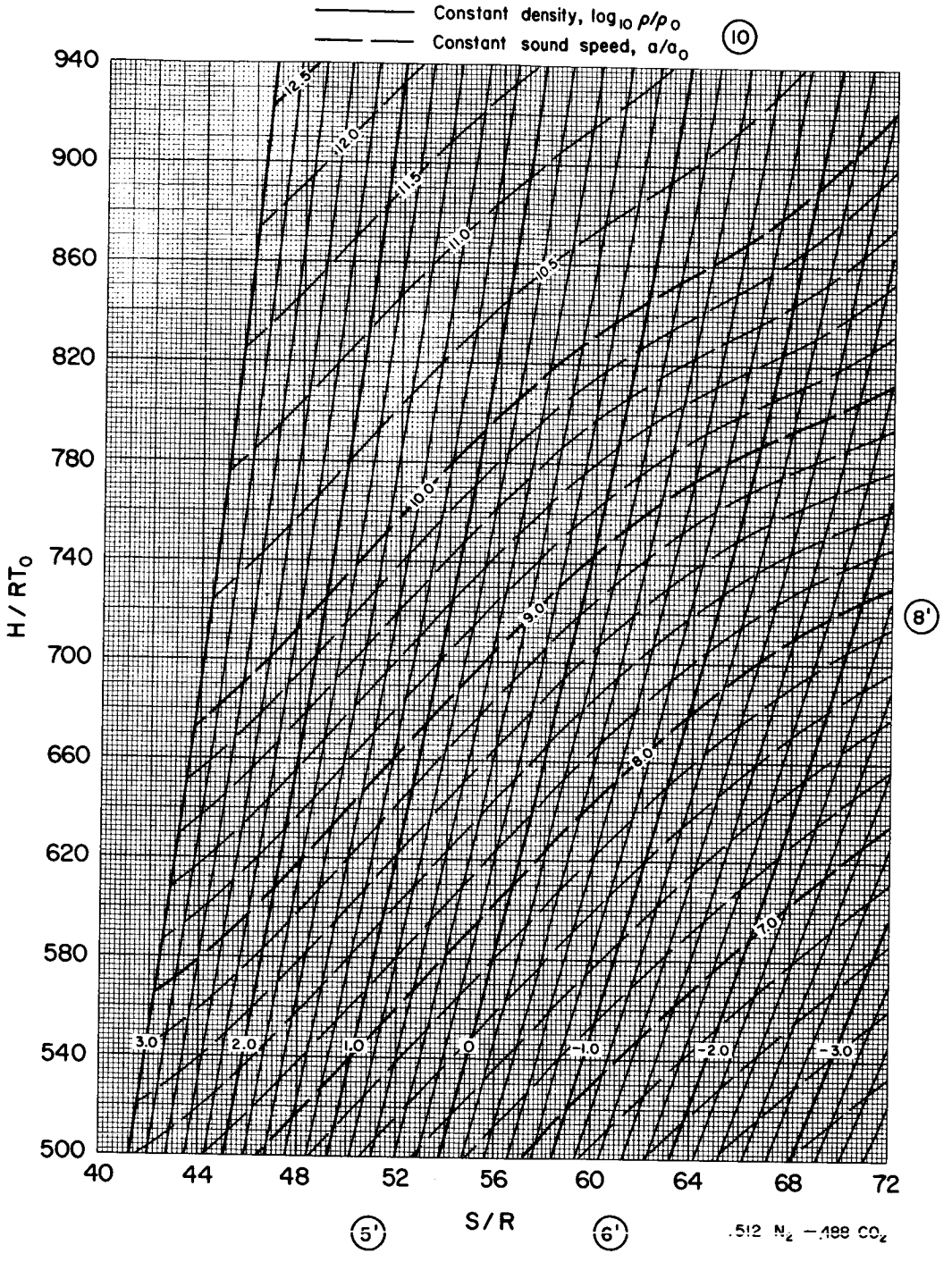
(f) Region 6 - Concluded.

Figure 20. - Continued.



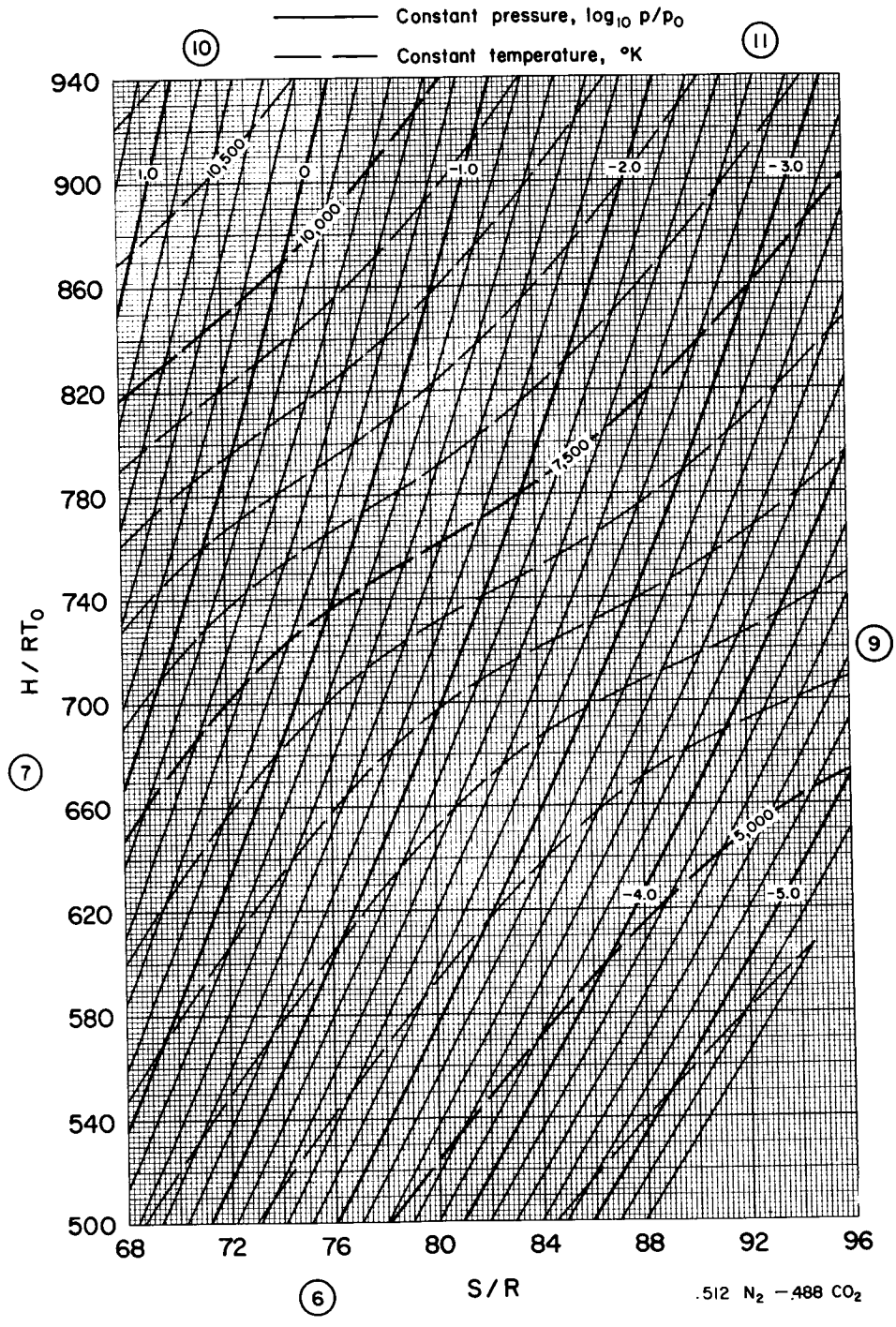
(g) Region 7.

Figure 20. - Continued.



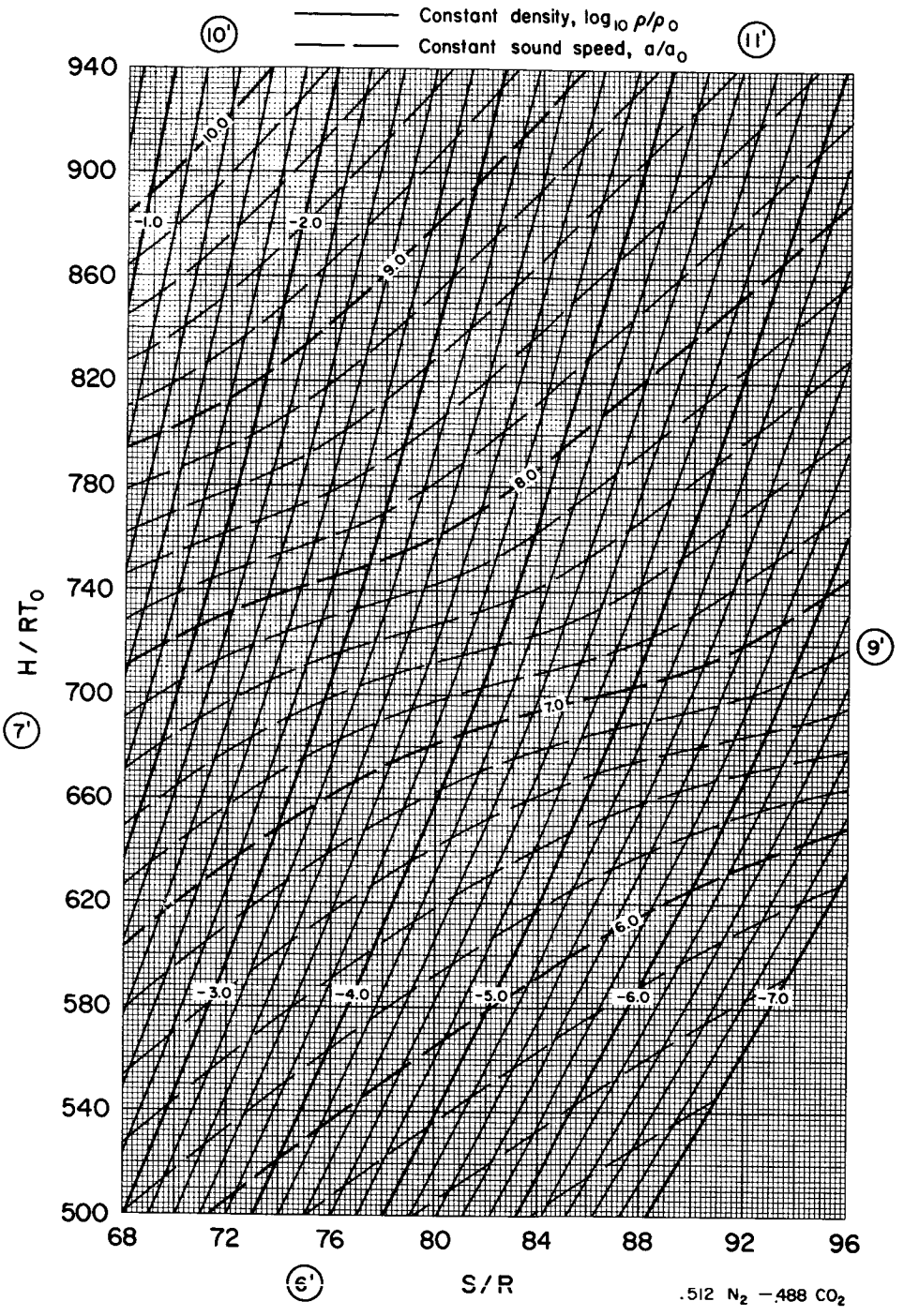
(g) Region 7 - Concluded.

Figure 20. - Continued.



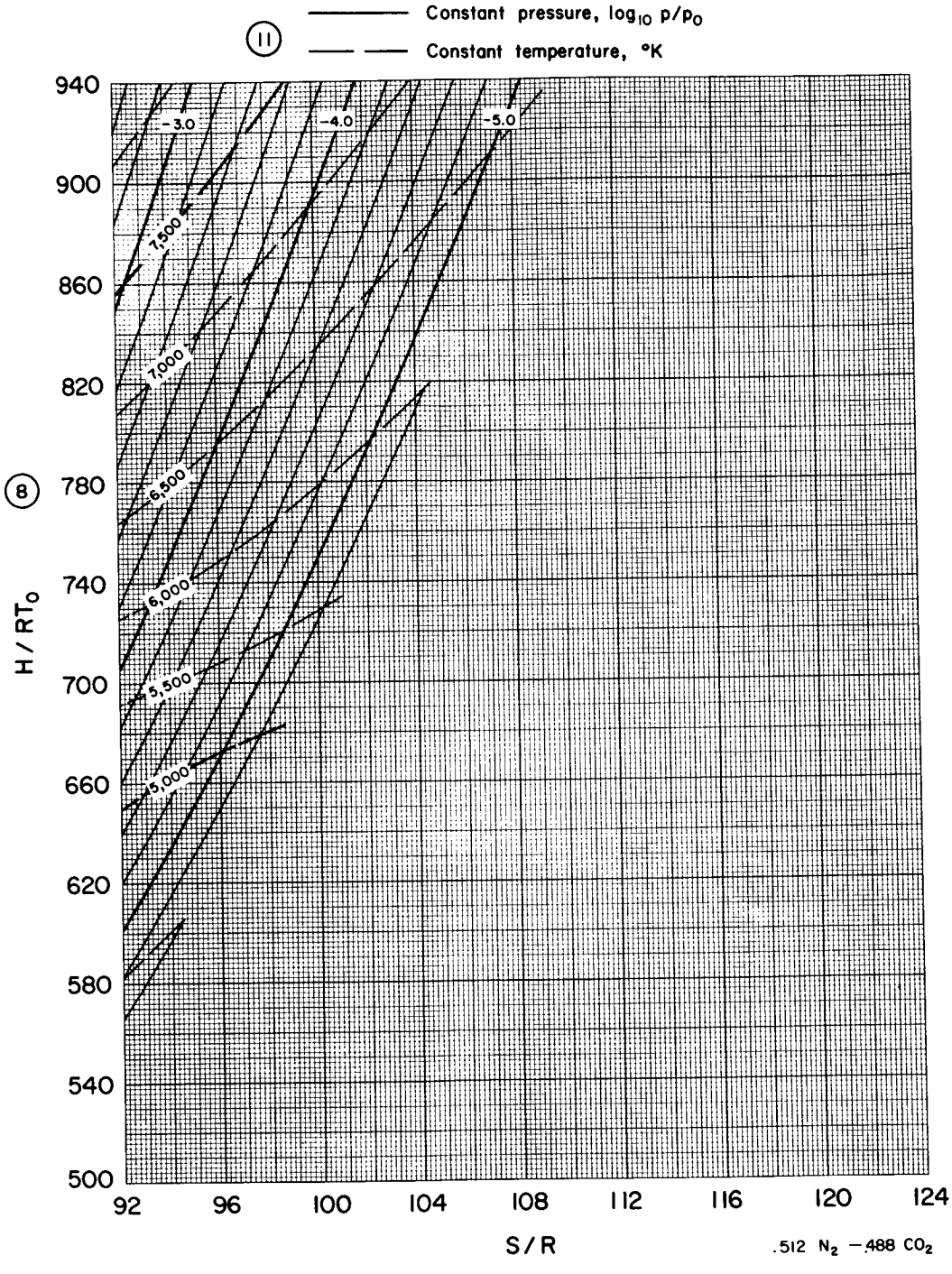
(h) Region 8.

Figure 20. - Continued.



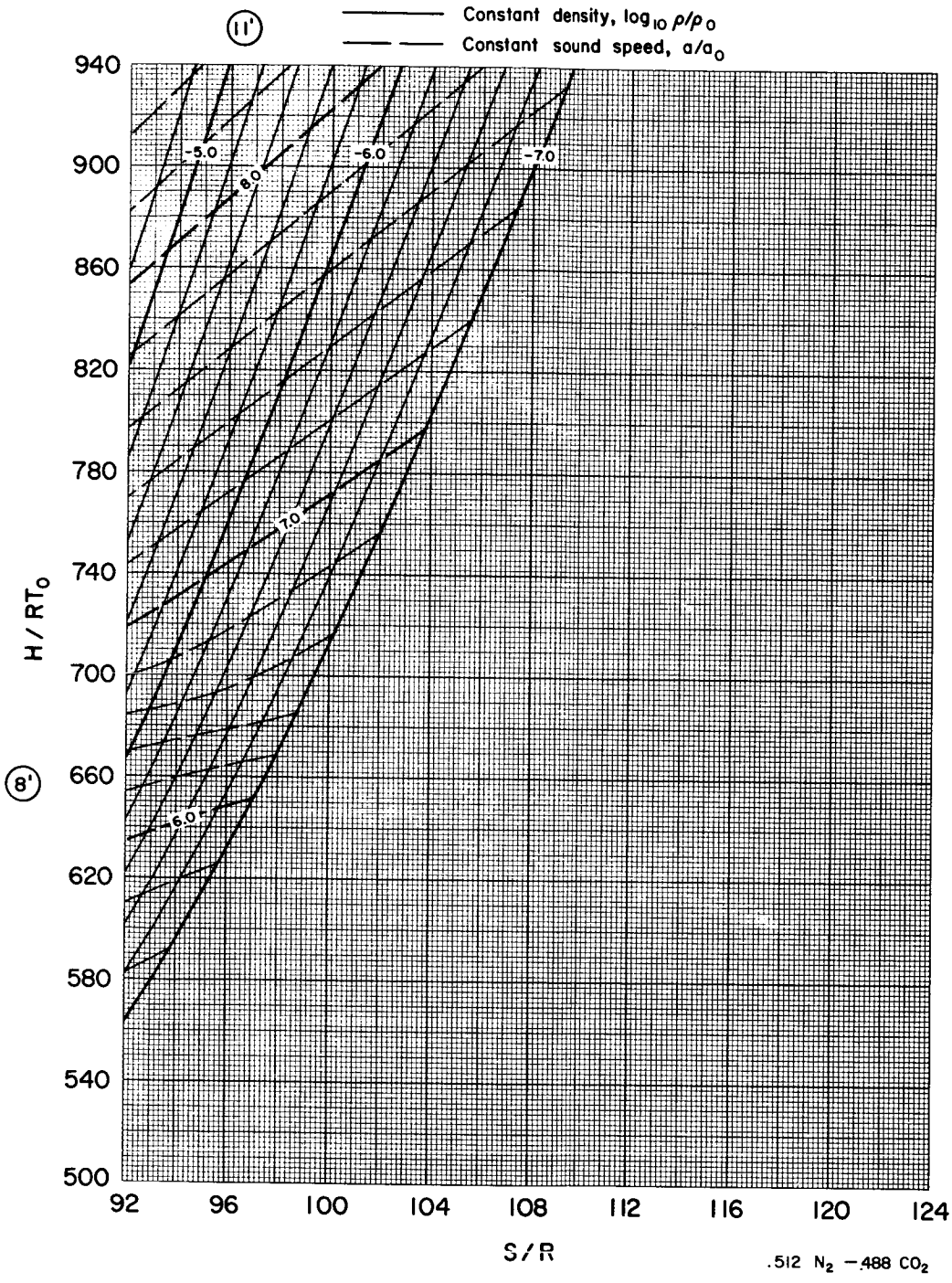
(h) Region 8 - Concluded.

Figure 20. - Continued.



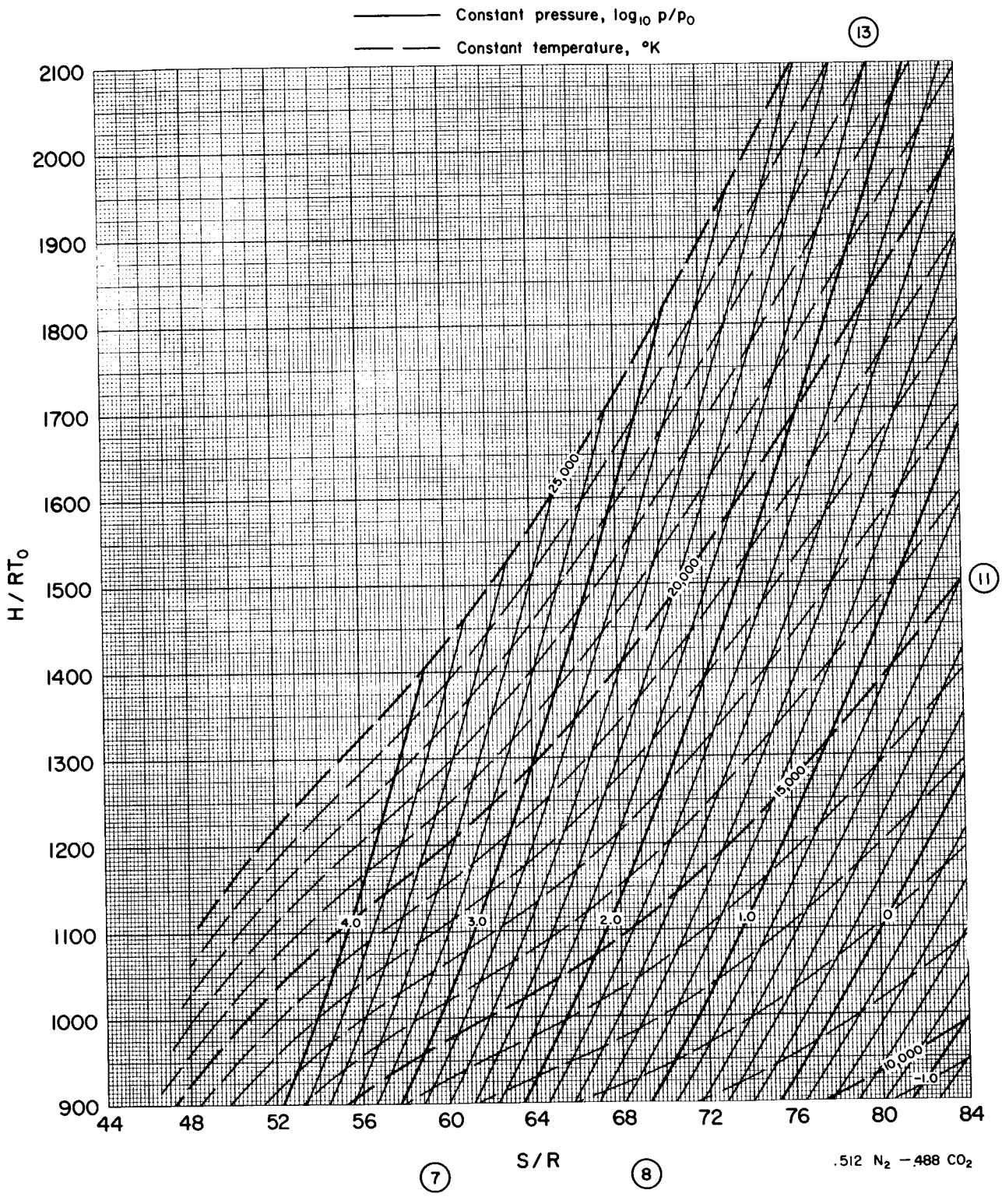
(i) Region 9.

Figure 20. - Continued.



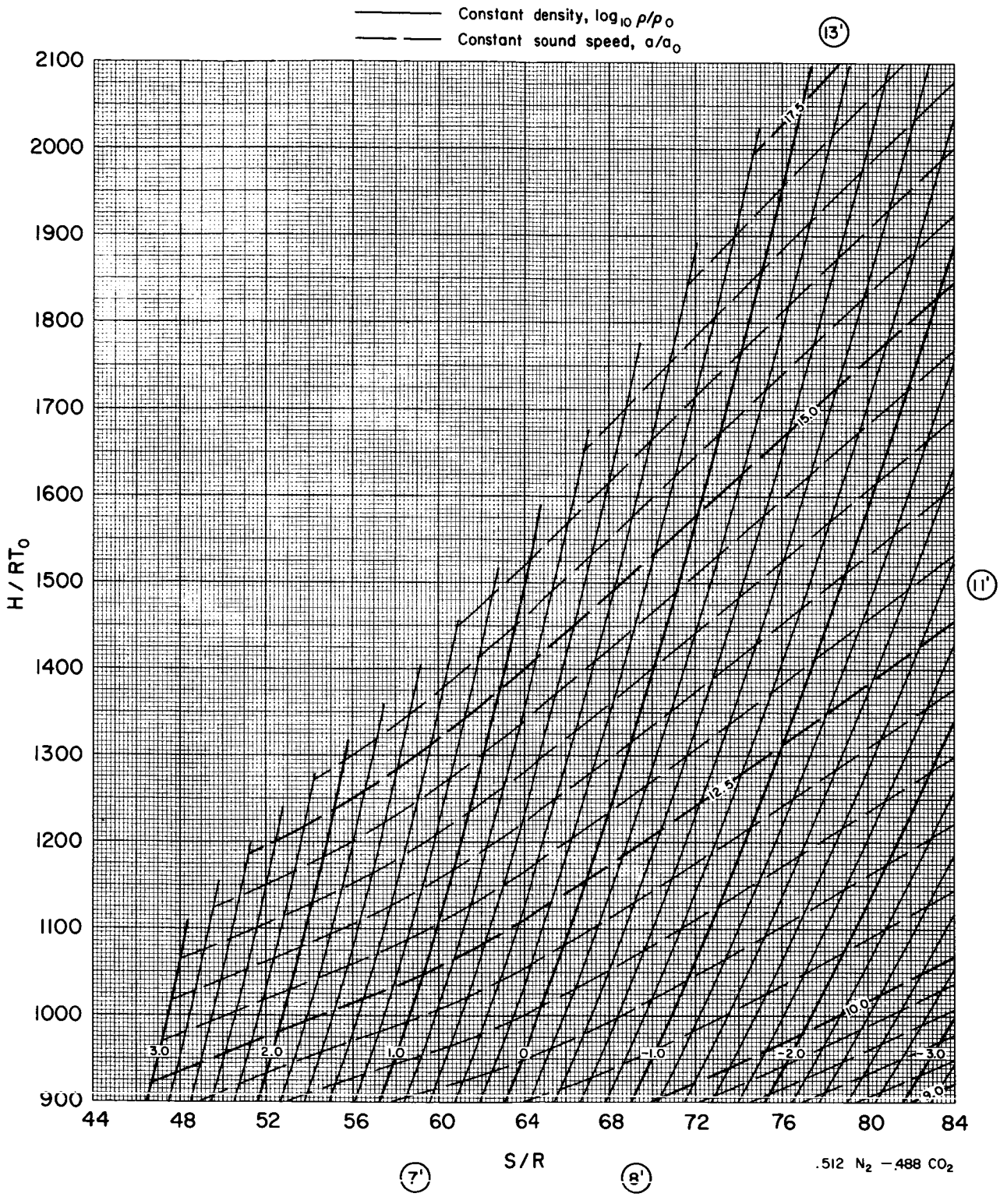
(i) Region 9 - Concluded.

Figure 20. - Continued.



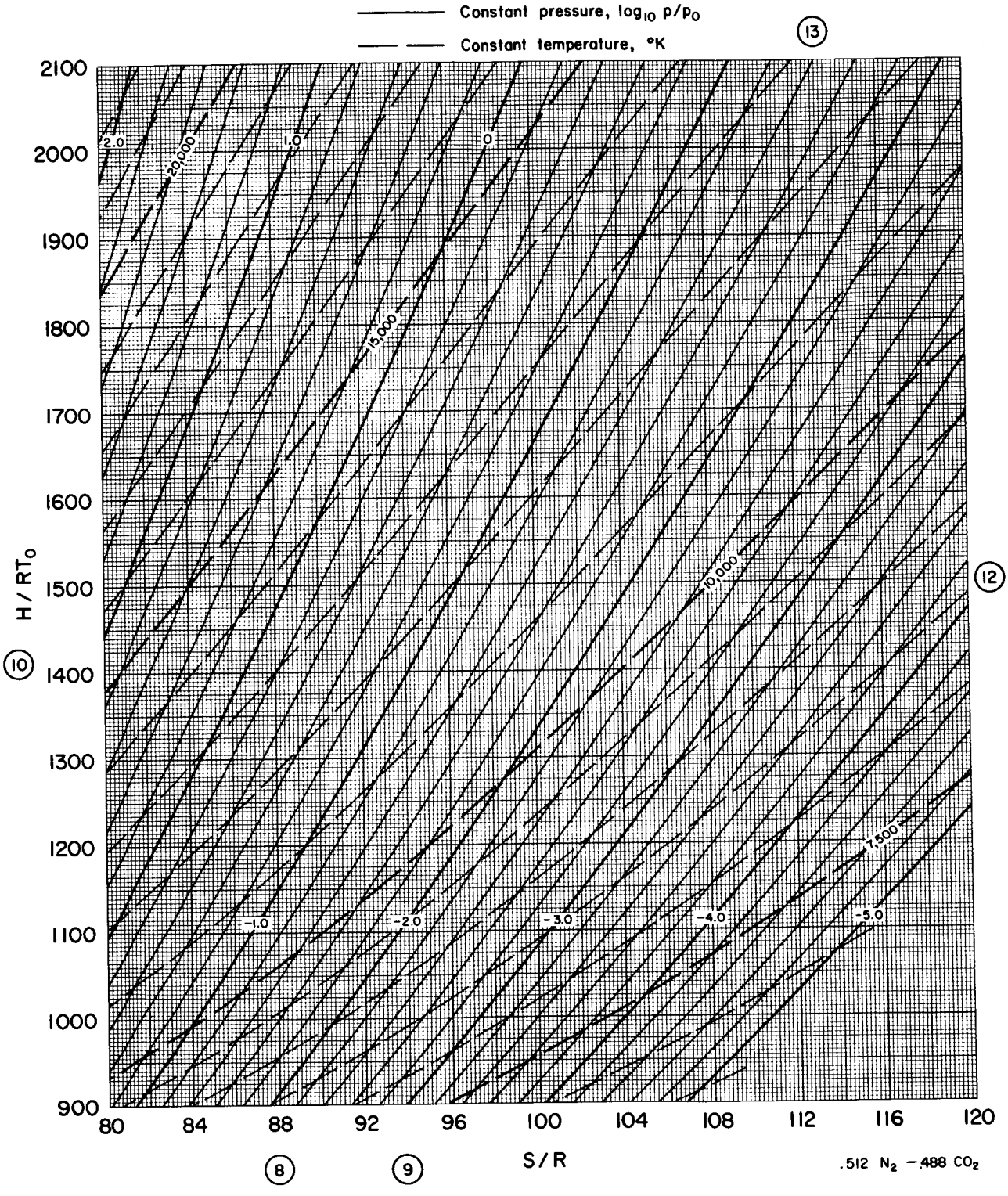
(j) Region 10.

Figure 20. - Continued.



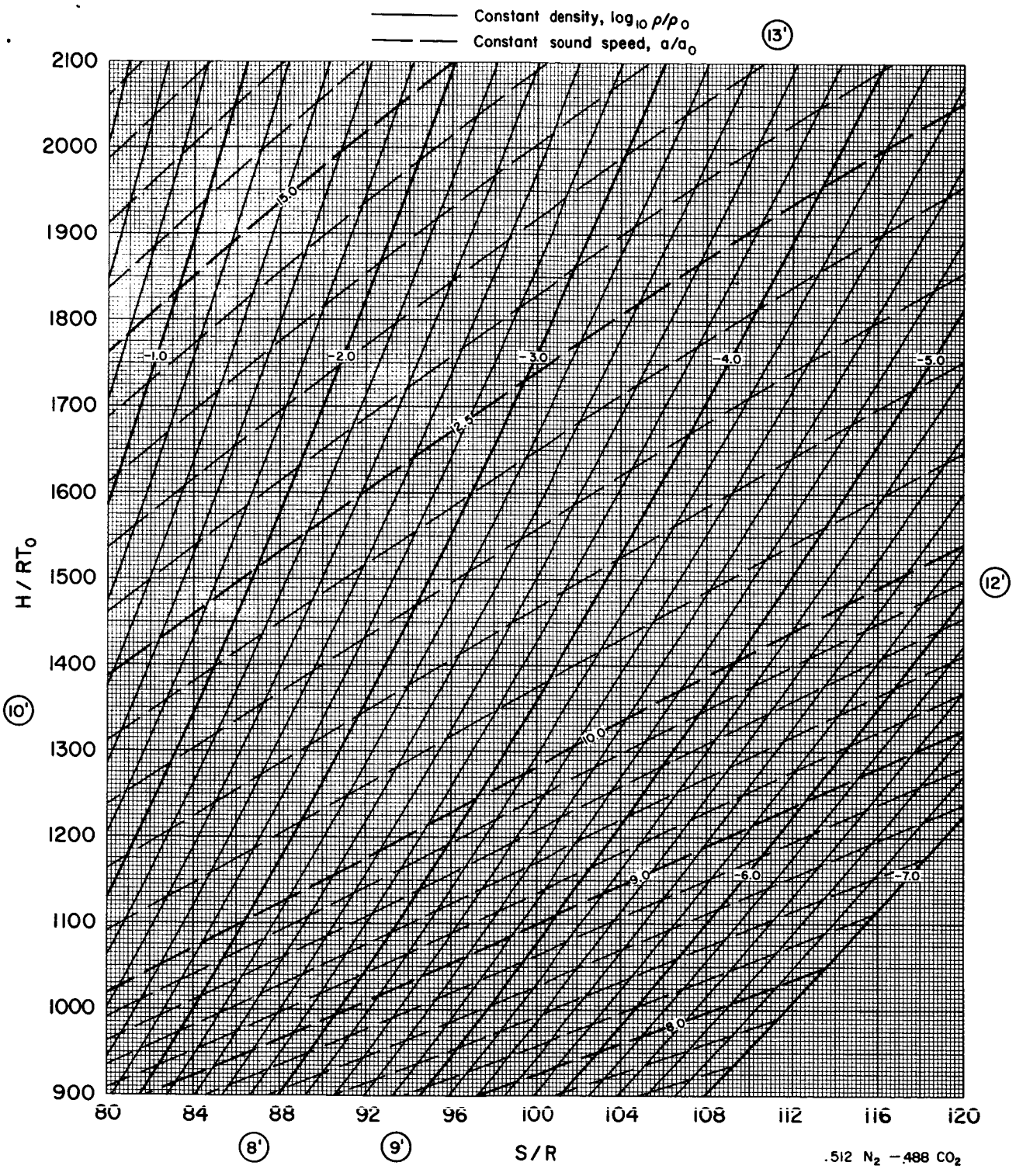
(j) Region 10 - Concluded.

Figure 20. - Continued.



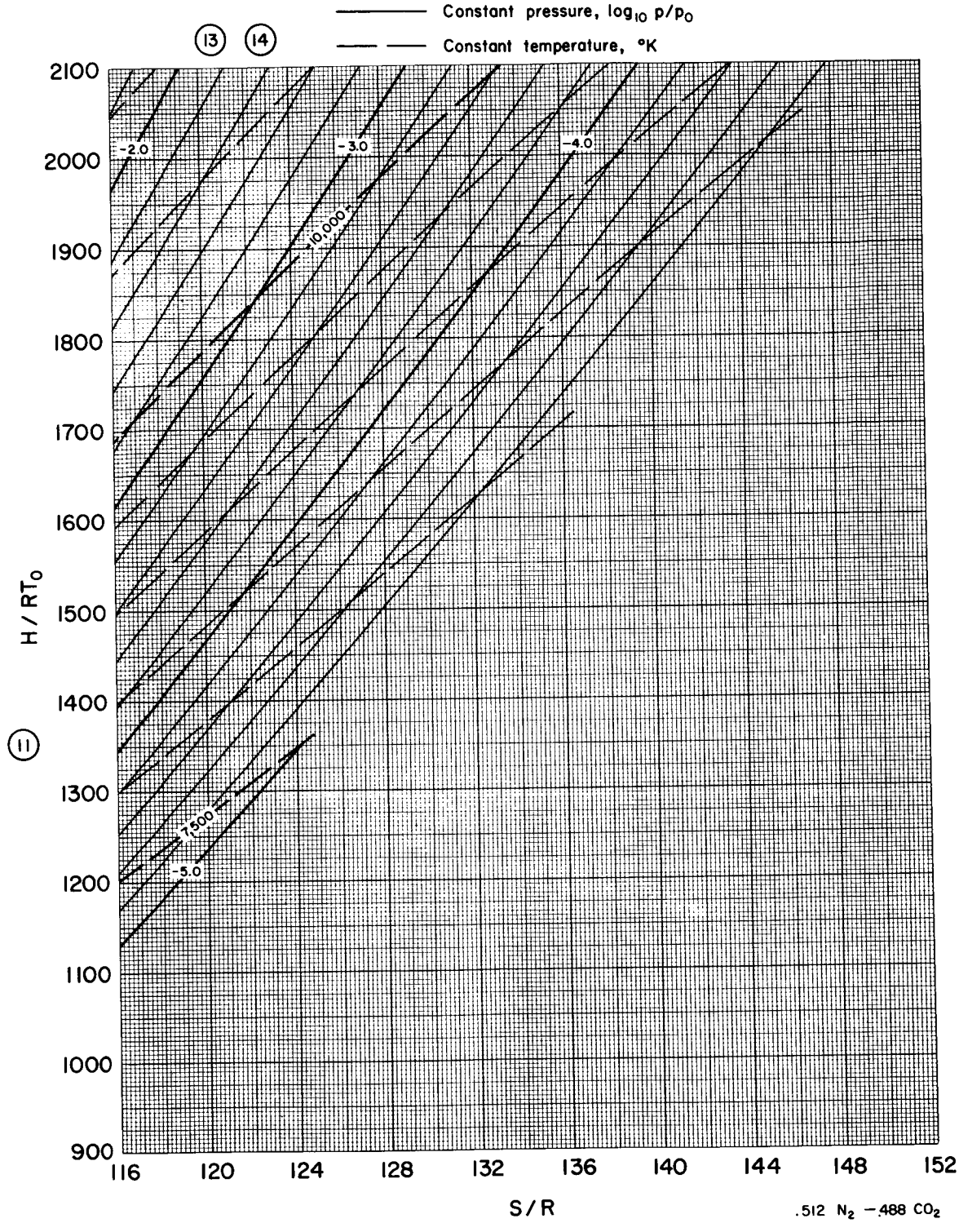
(k) Region 11.

Figure 20. - Continued.



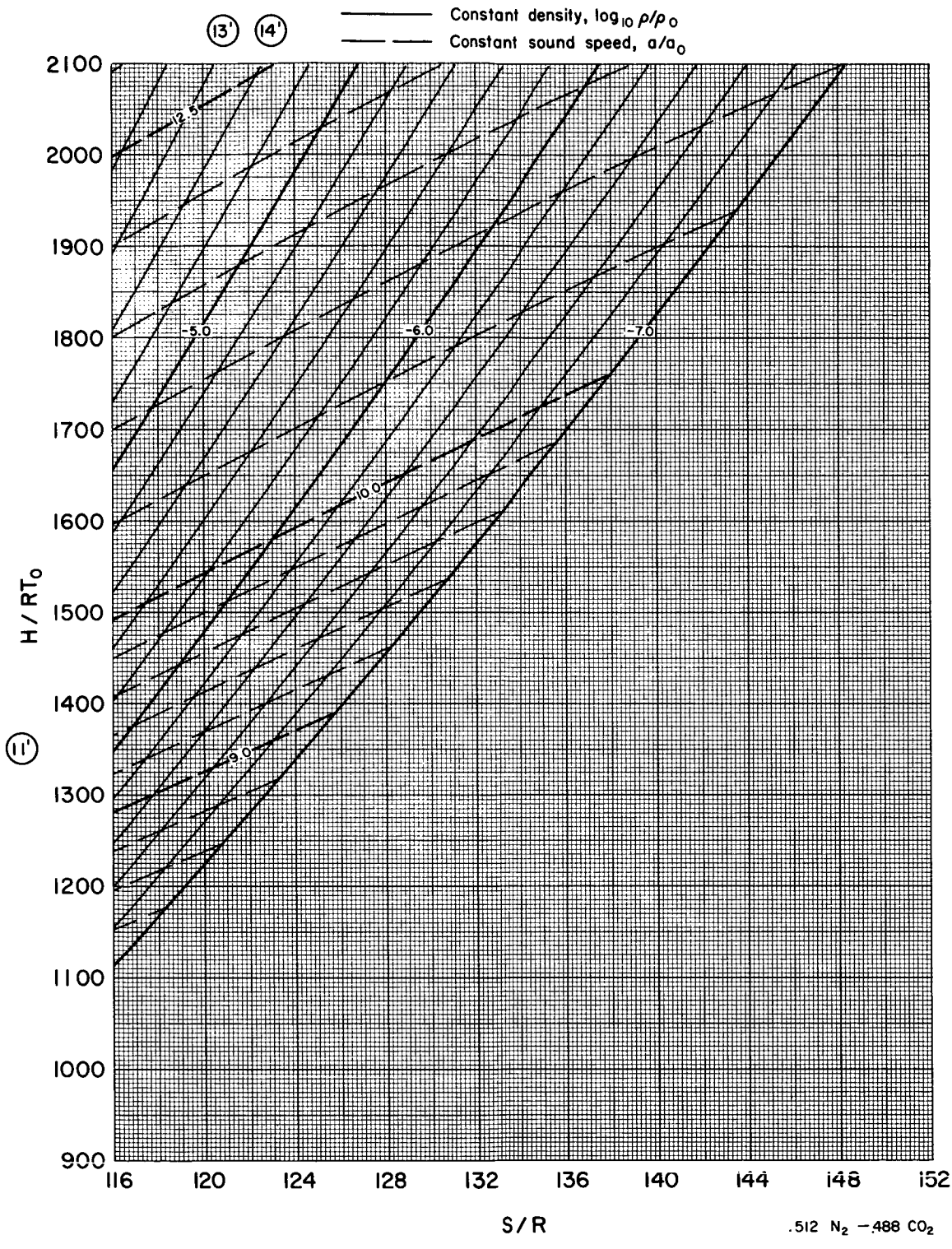
(k) Region 11 - Concluded.

Figure 20. - Continued.



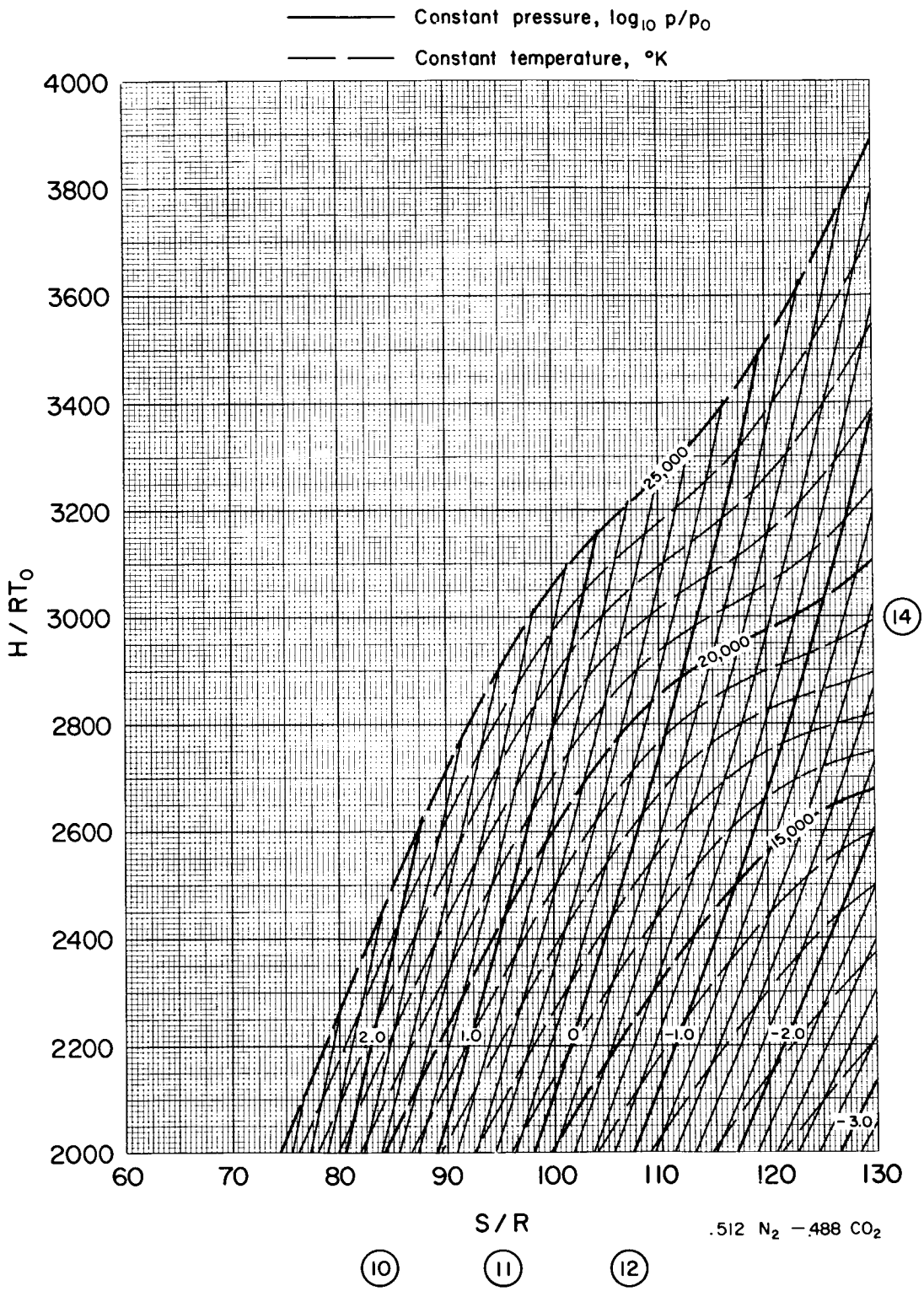
(l) Region 12.

Figure 20. - Continued.



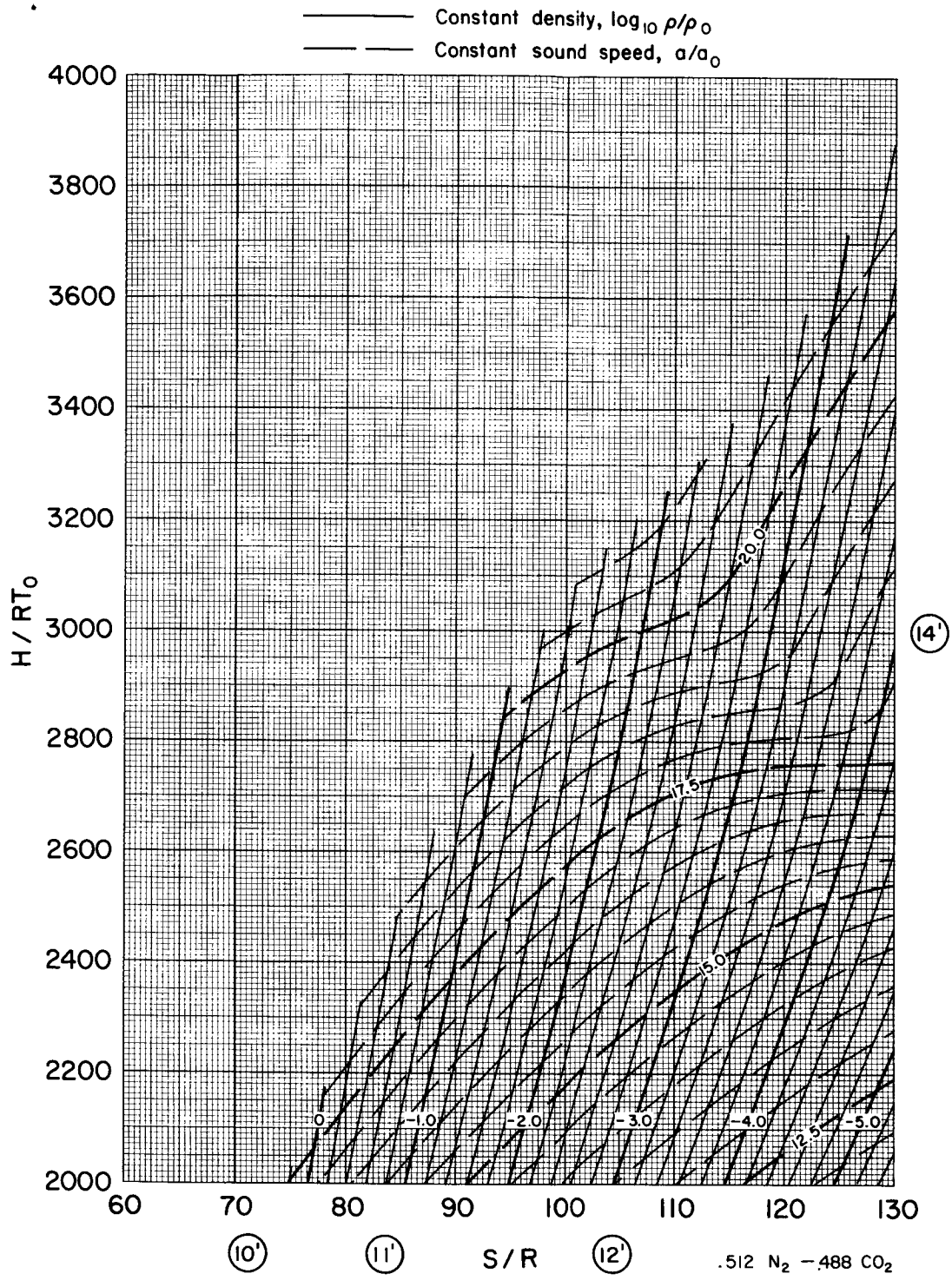
(l) Region 12 - Concluded.

Figure 20. - Continued.



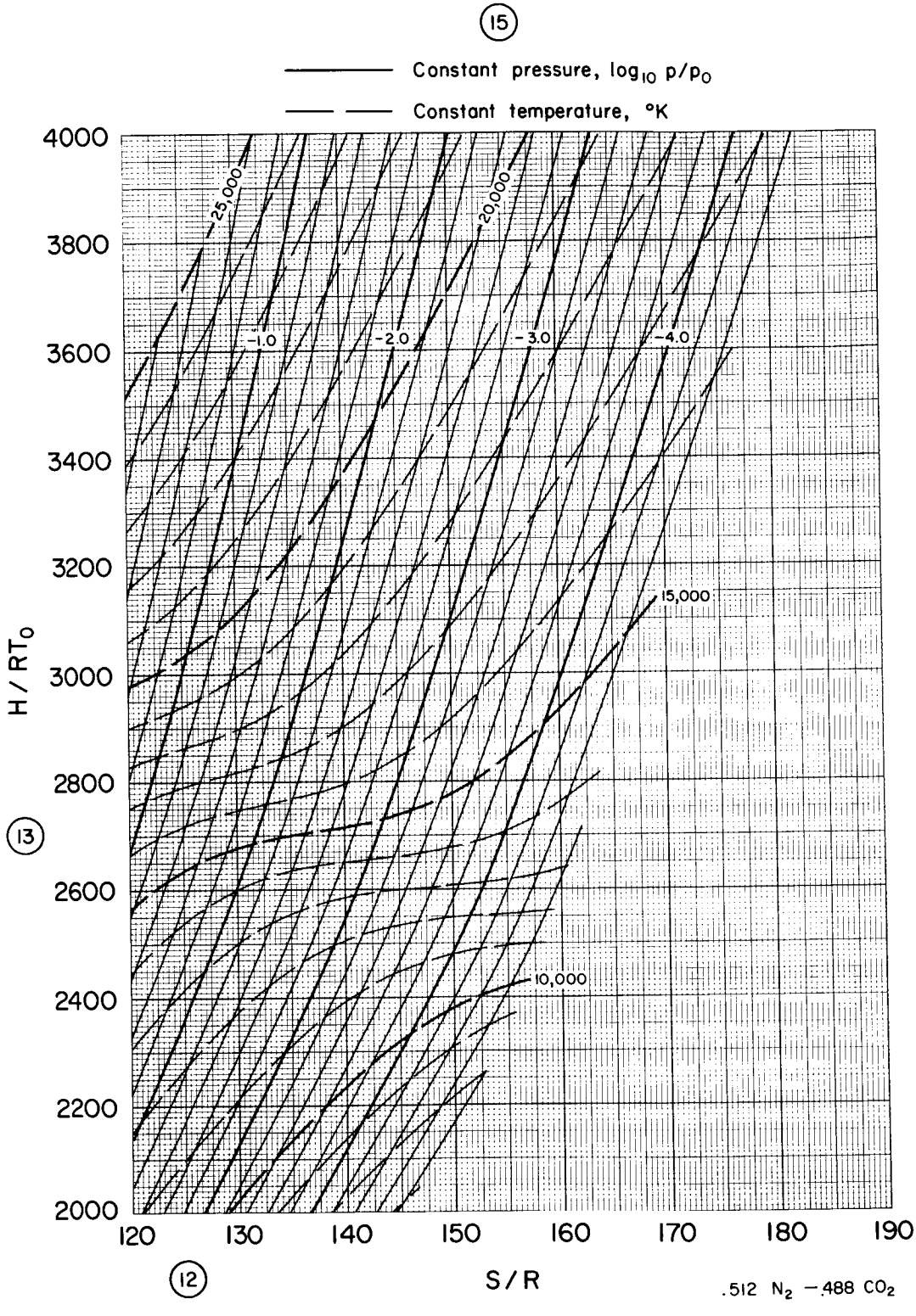
(m) Region 13.

Figure 20. - Continued.



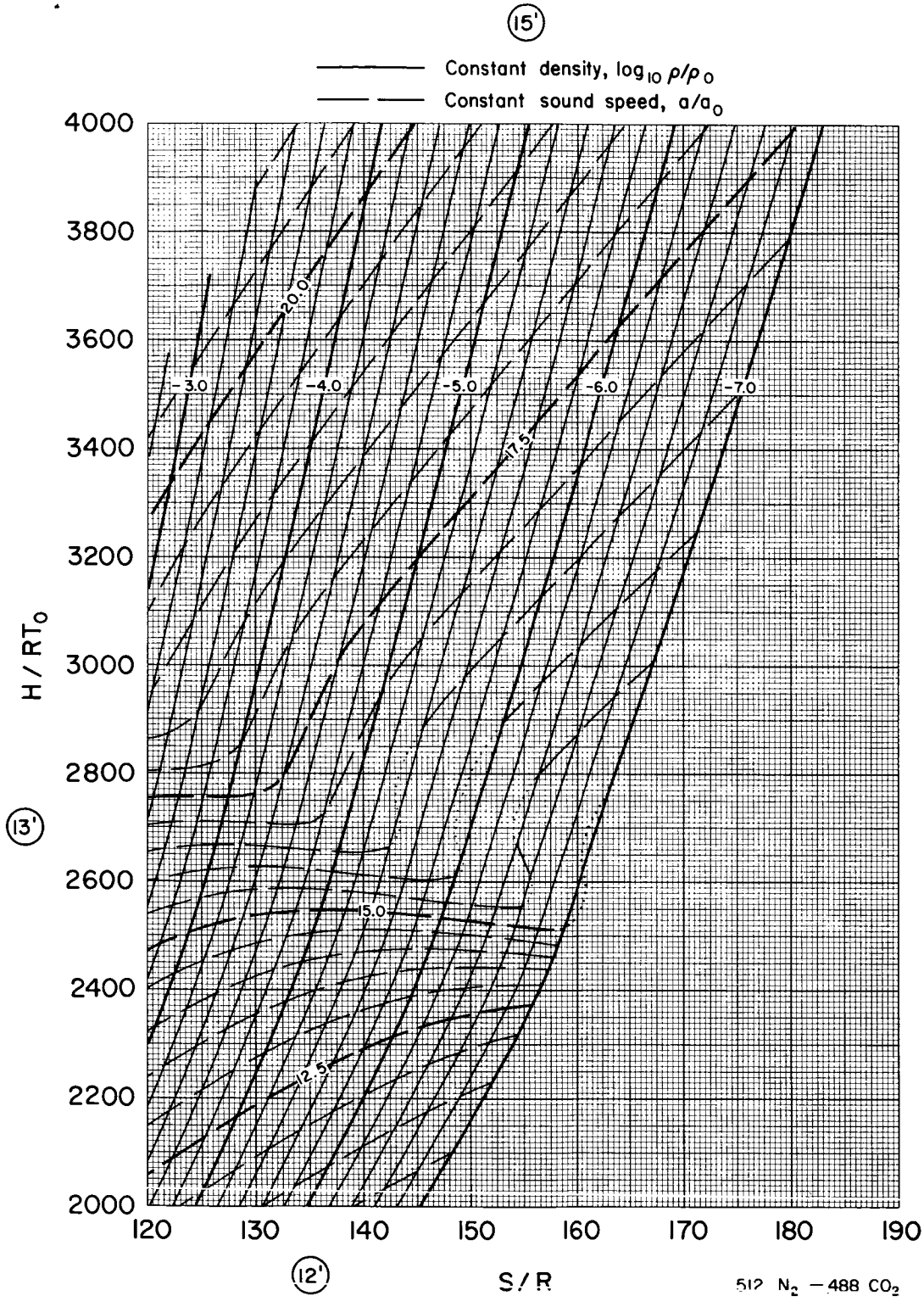
(m) Region 13 - Concluded.

Figure 20. - Continued.



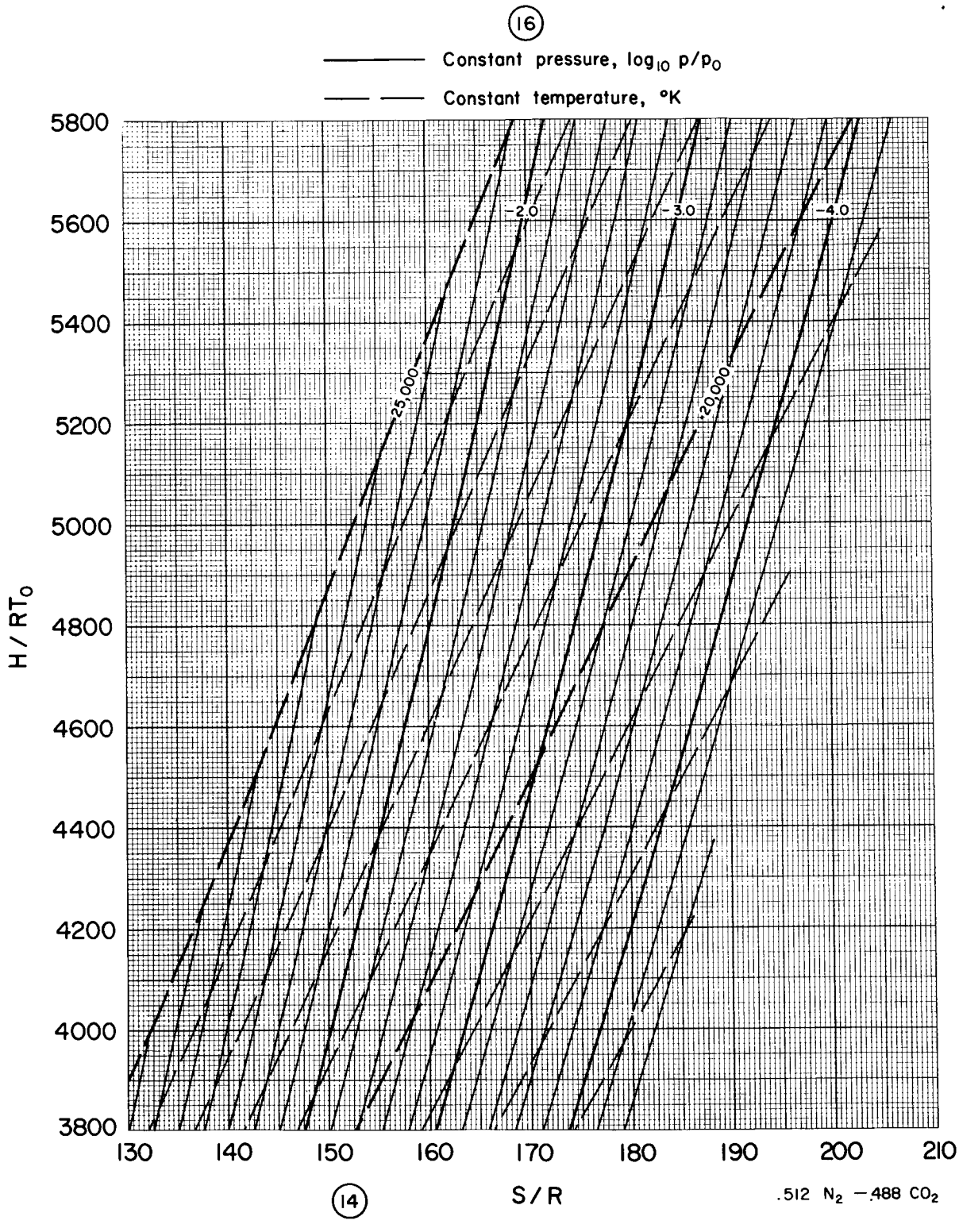
(n) Region 14.

Figure 20. - Continued.



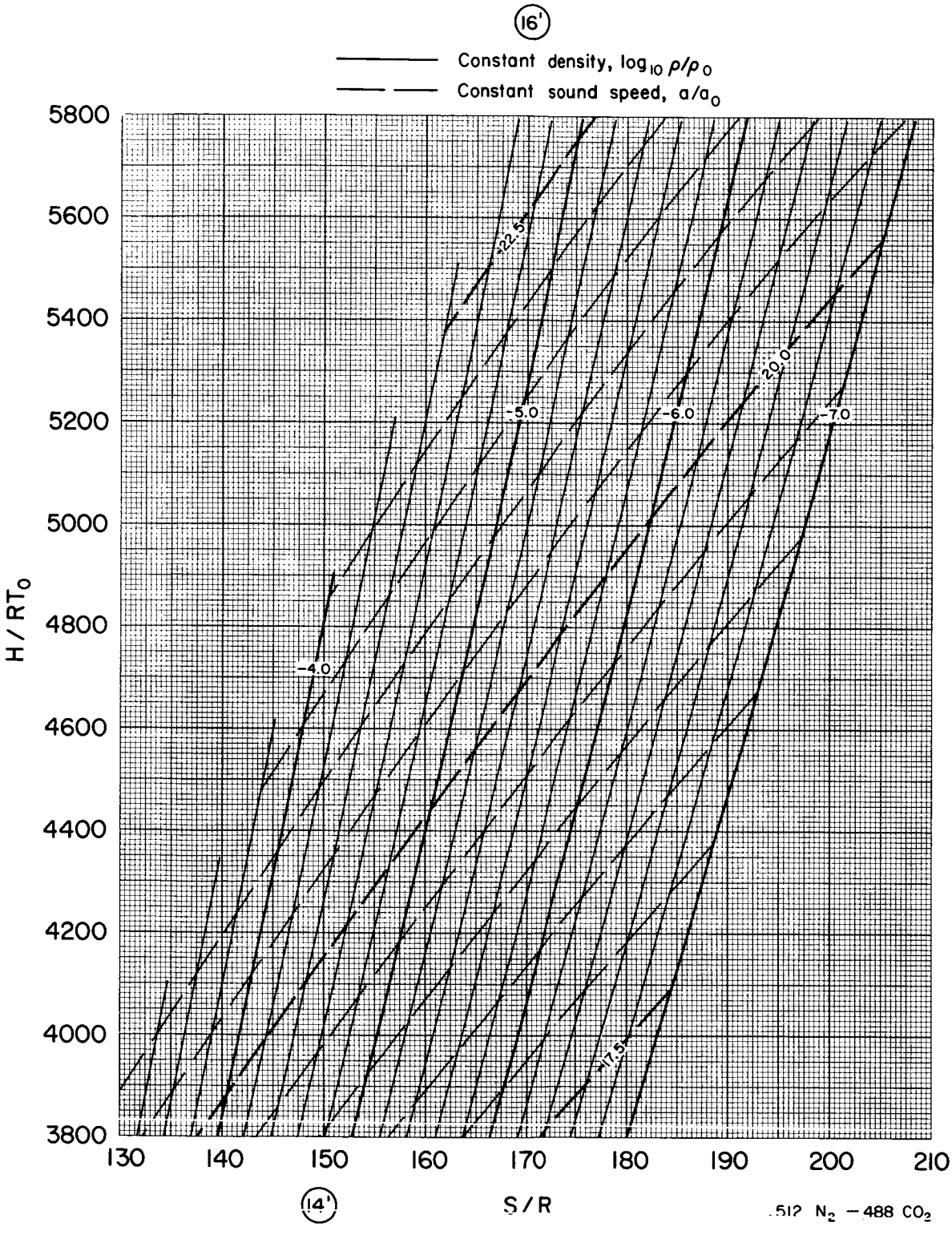
(n) Region 14 - Concluded.

Figure 20. - Continued.



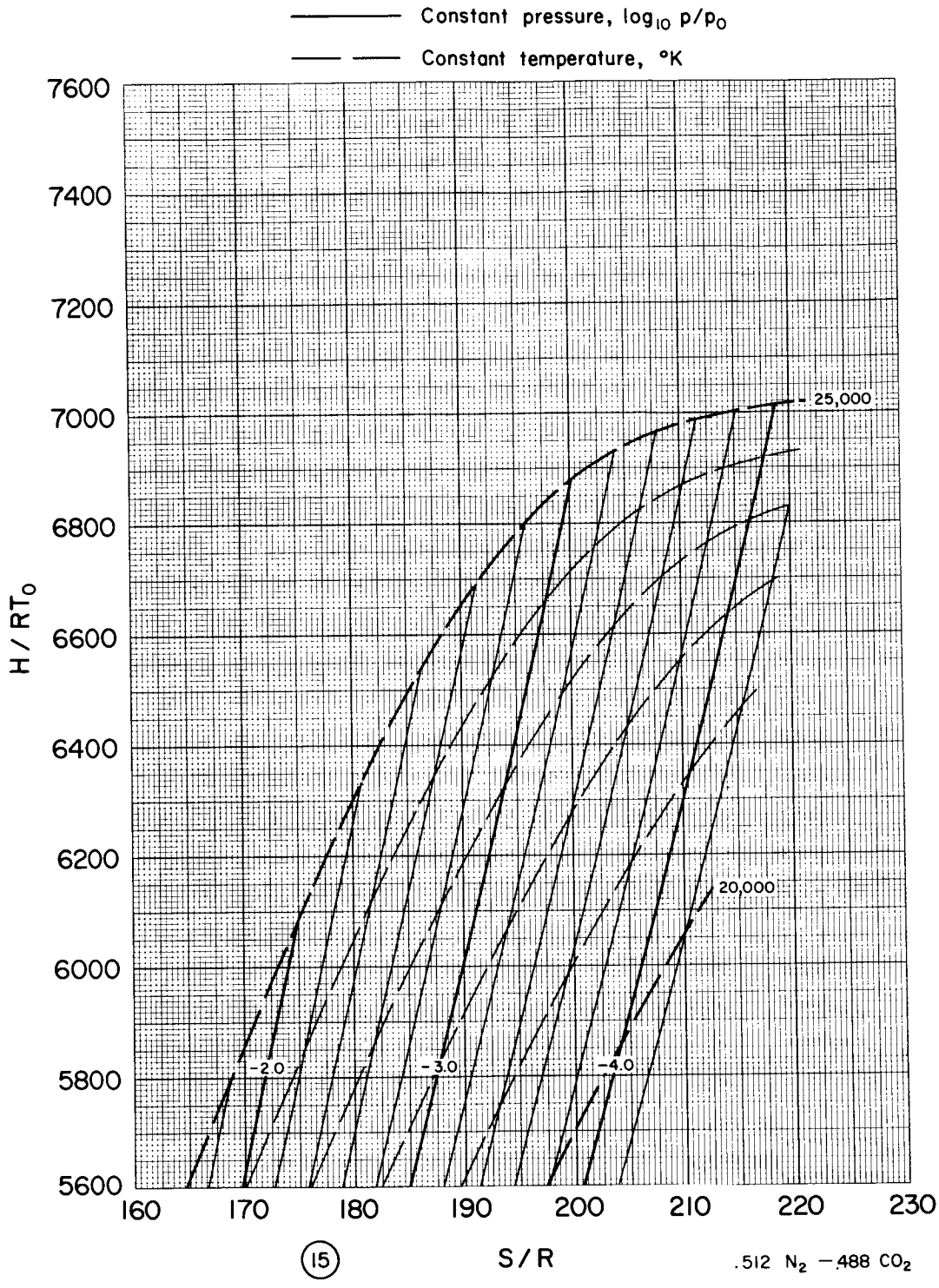
(o) Region 15.

Figure 20. - Continued.



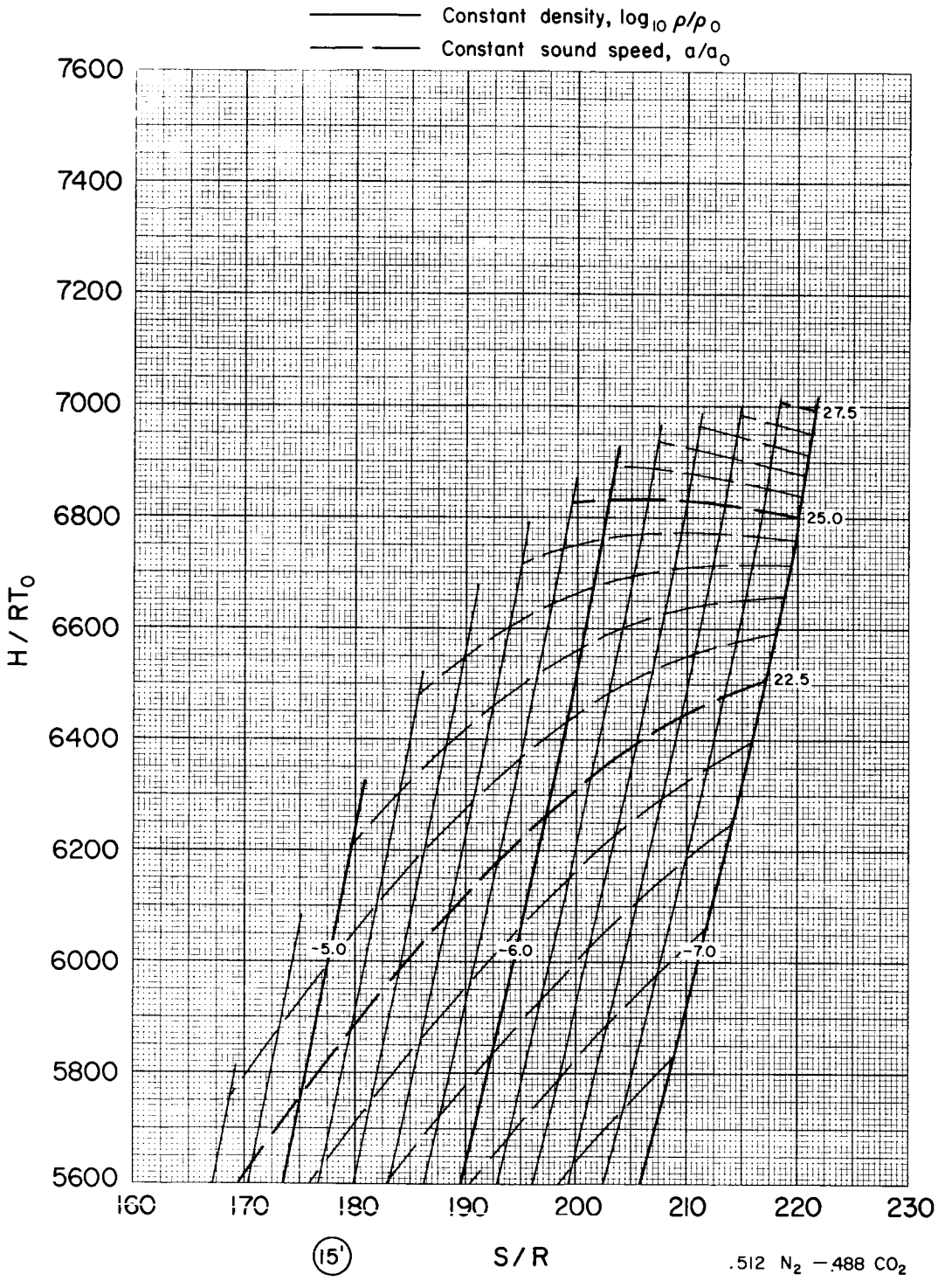
(o) Region 15 - Concluded.

Figure 20. - Continued.



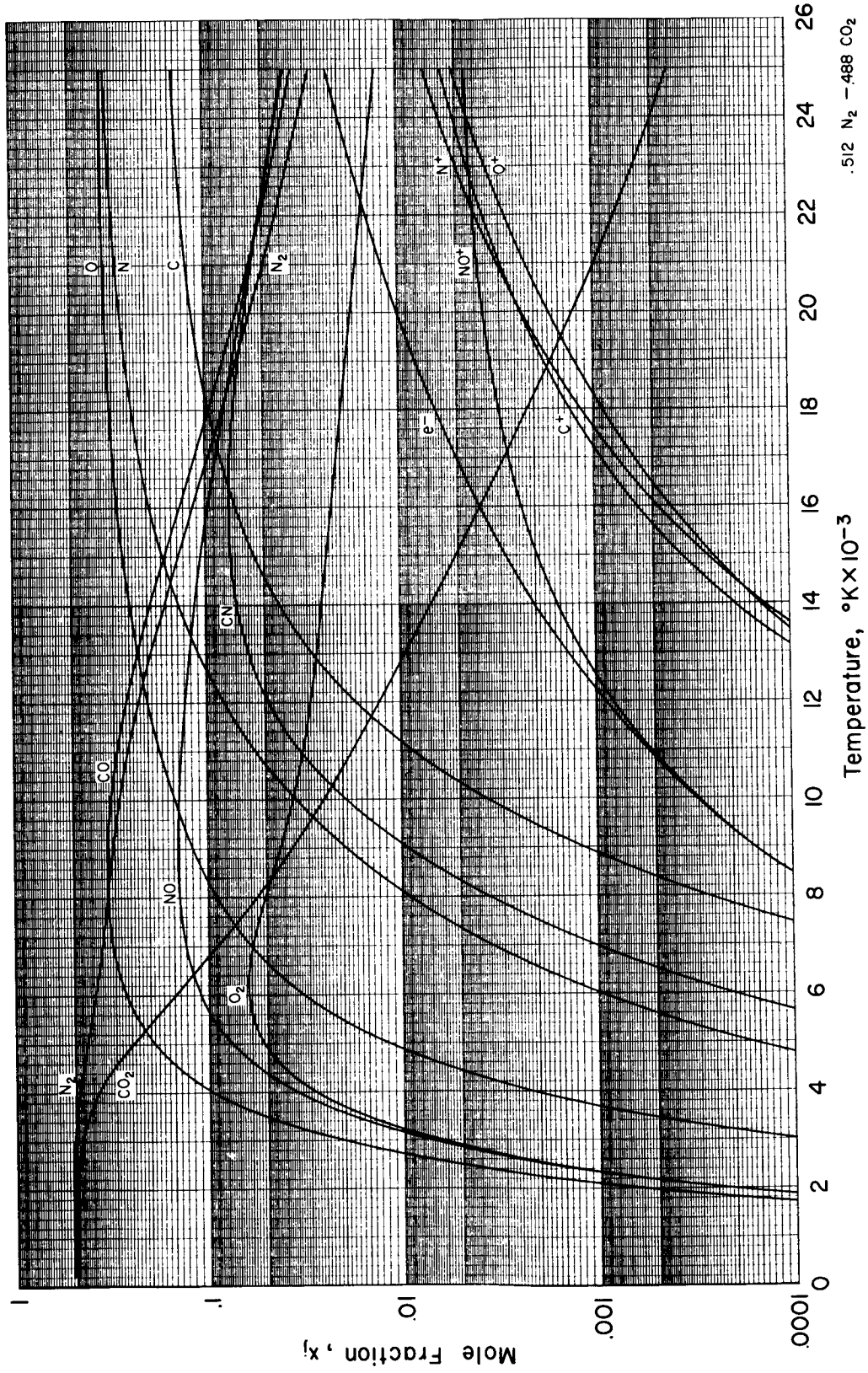
(p) Region 16.

Figure 20. - Continued.



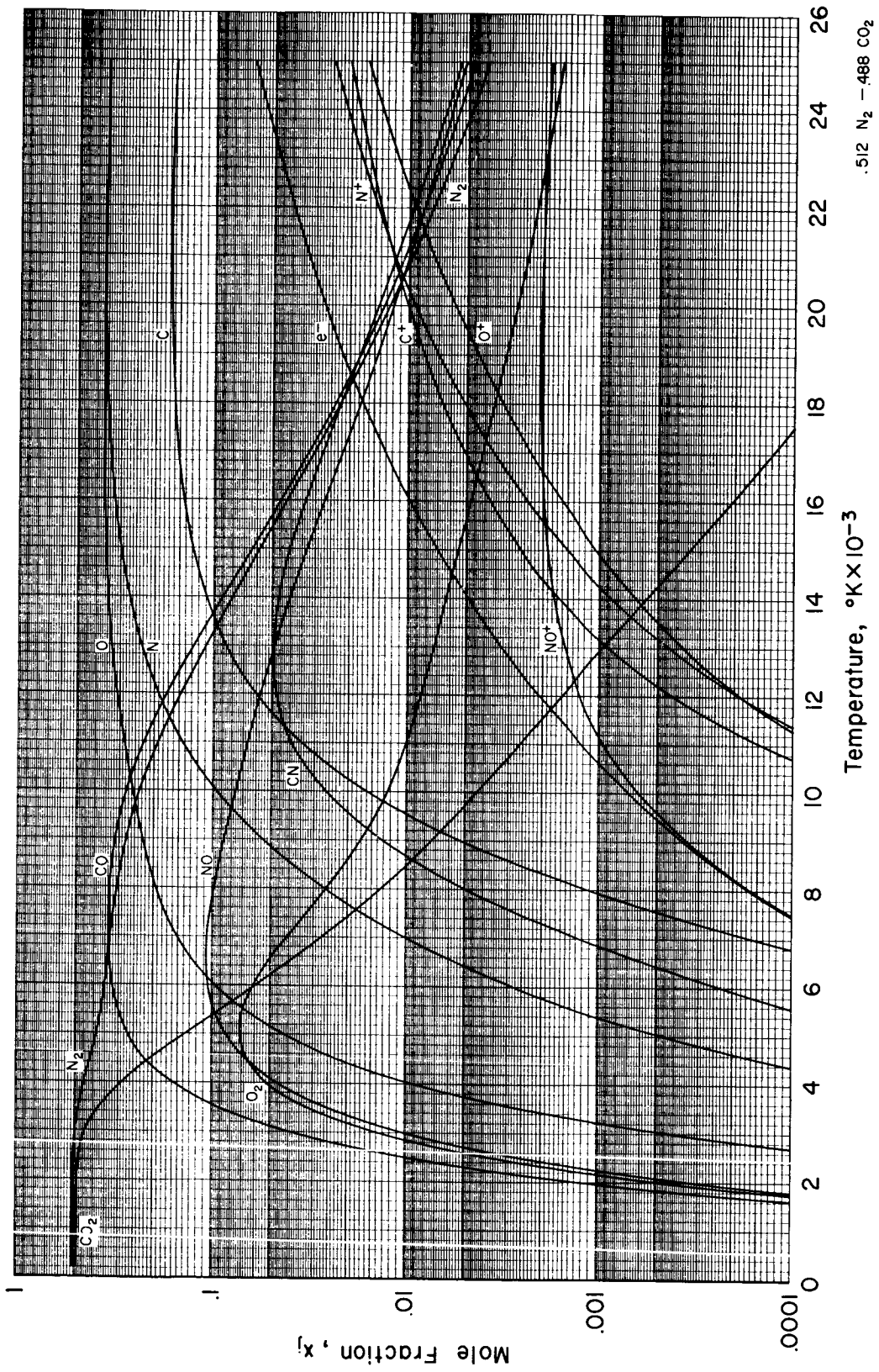
(p) Region 16 - Concluded.

Figure 20. - Concluded.



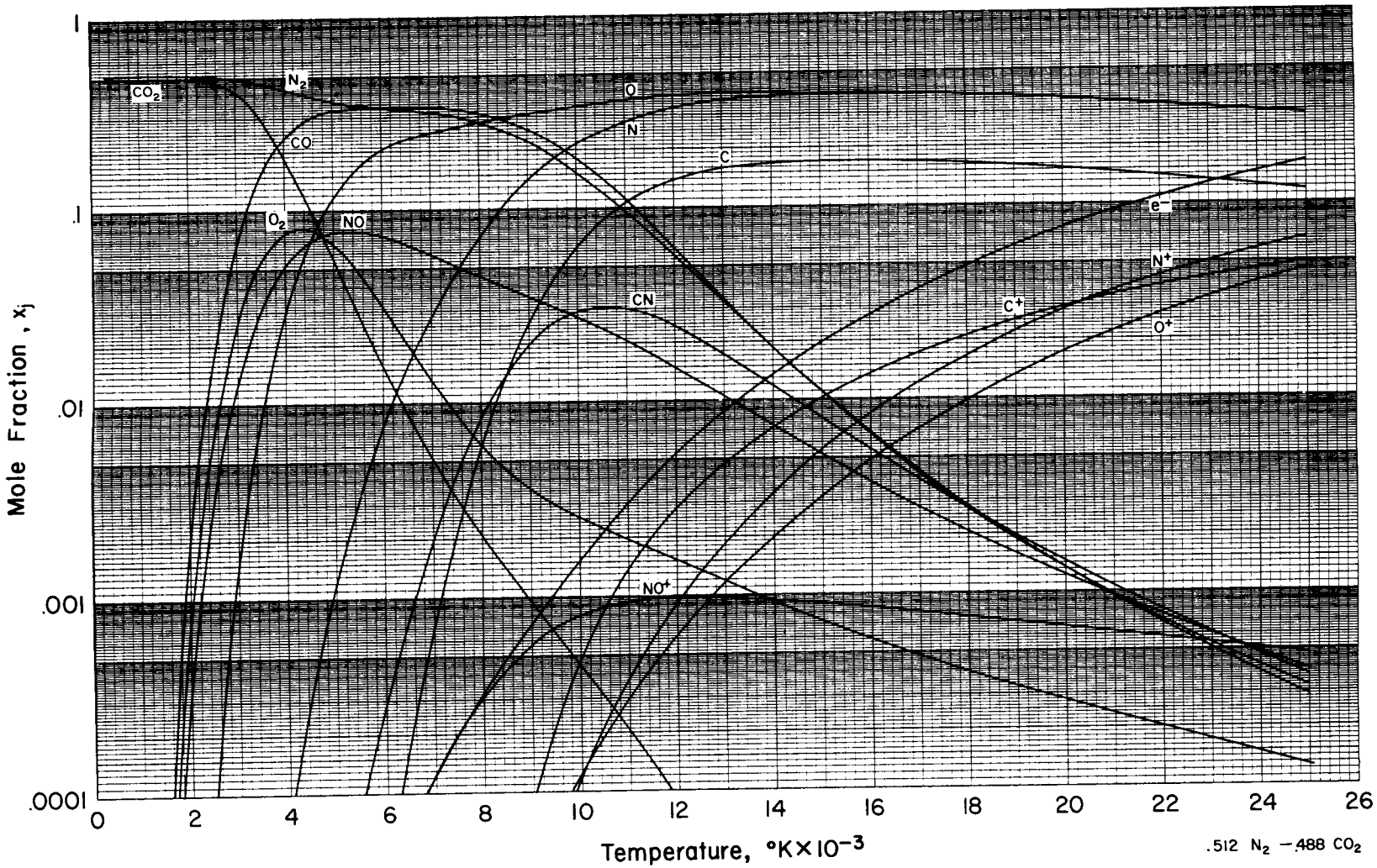
(a) $\rho/\rho_0 = 10^3$

Figure 21. - Equilibrium chemical composition.



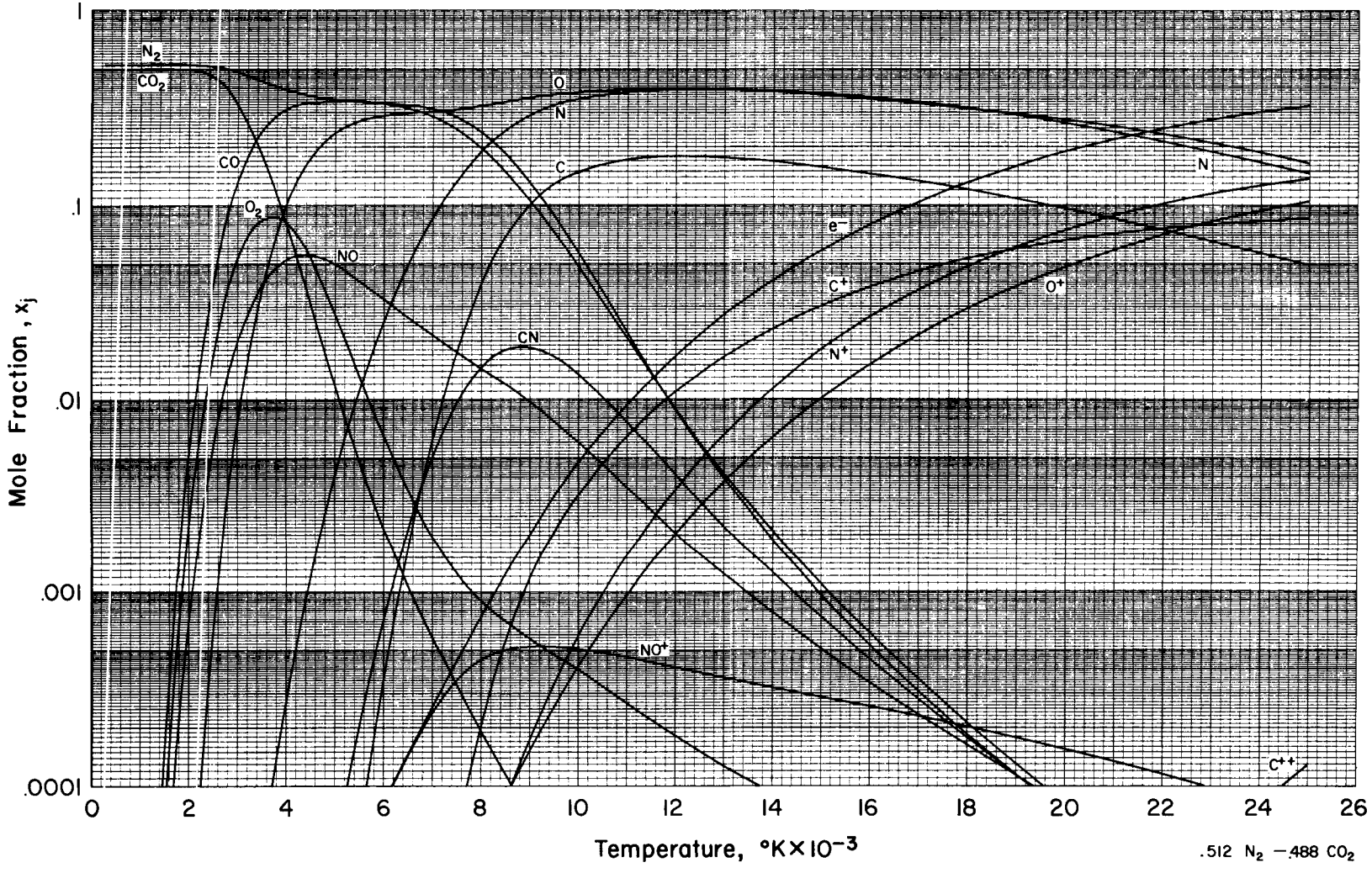
(b) $\rho/\rho_0 = 10^2$

Figure 21. - Continued.



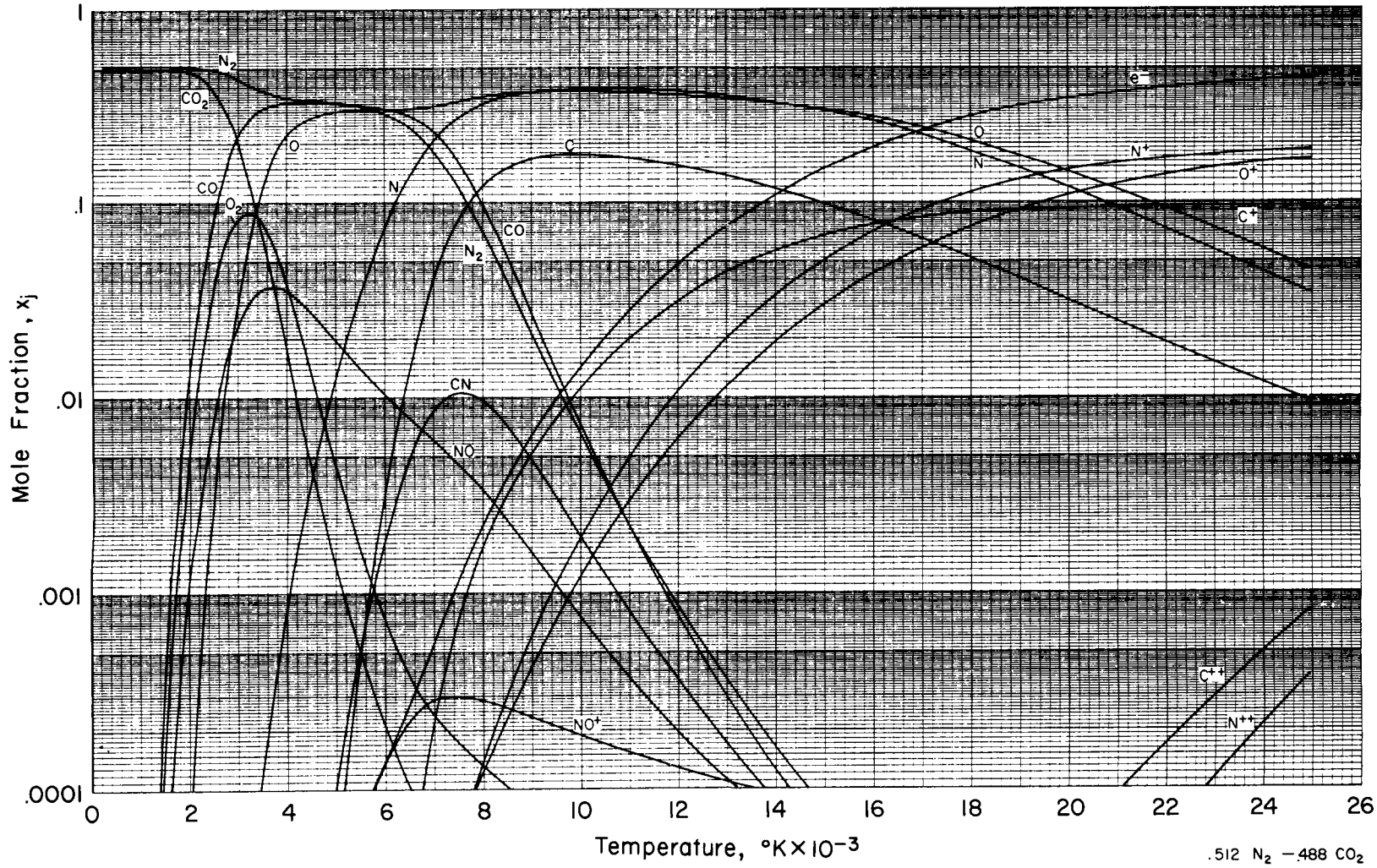
(c) $\rho/\rho_0 = 10$

Figure 21. - Continued.



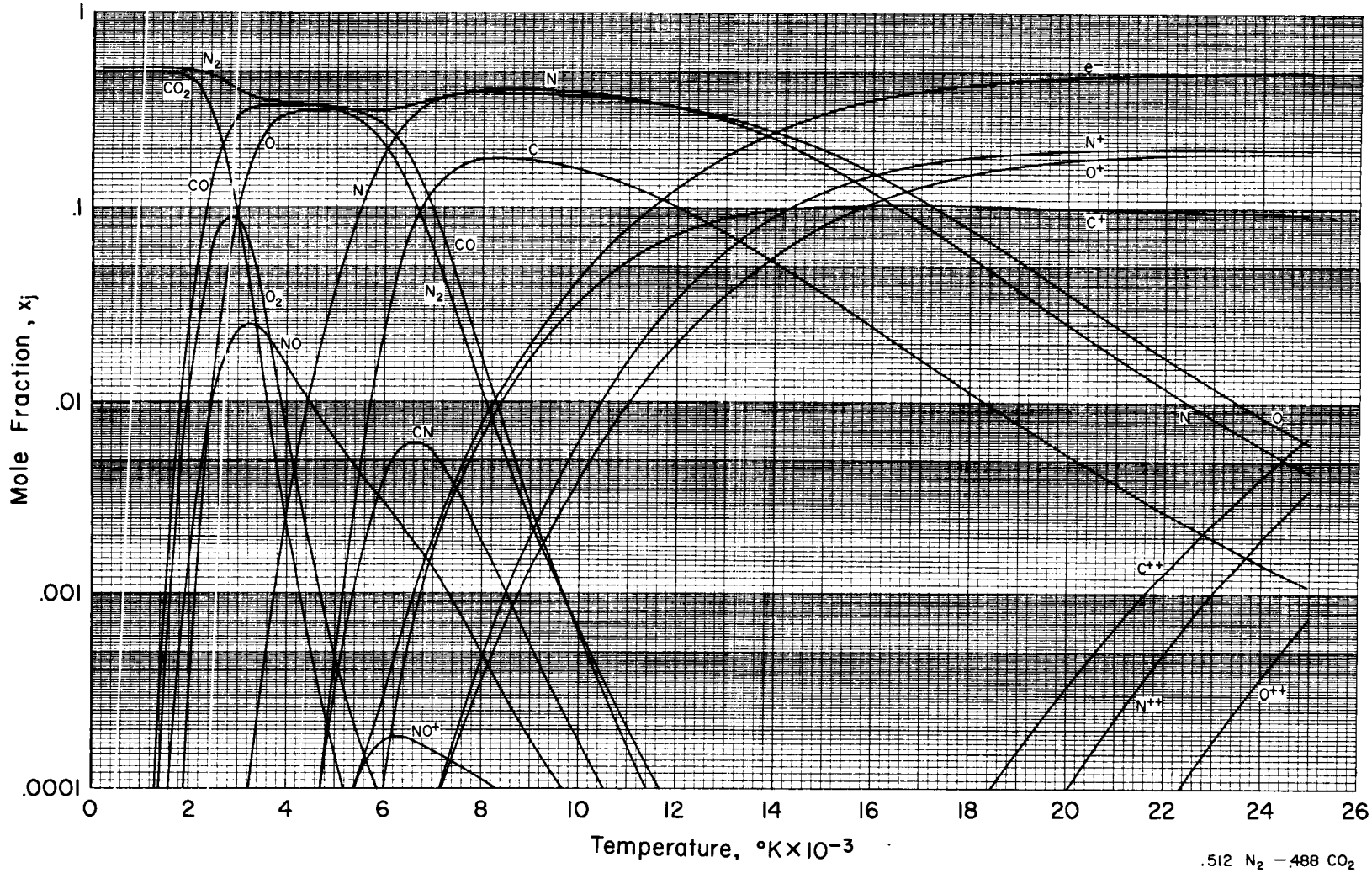
(d) $\rho/\rho_o = 1$

Figure 21. - Continued.



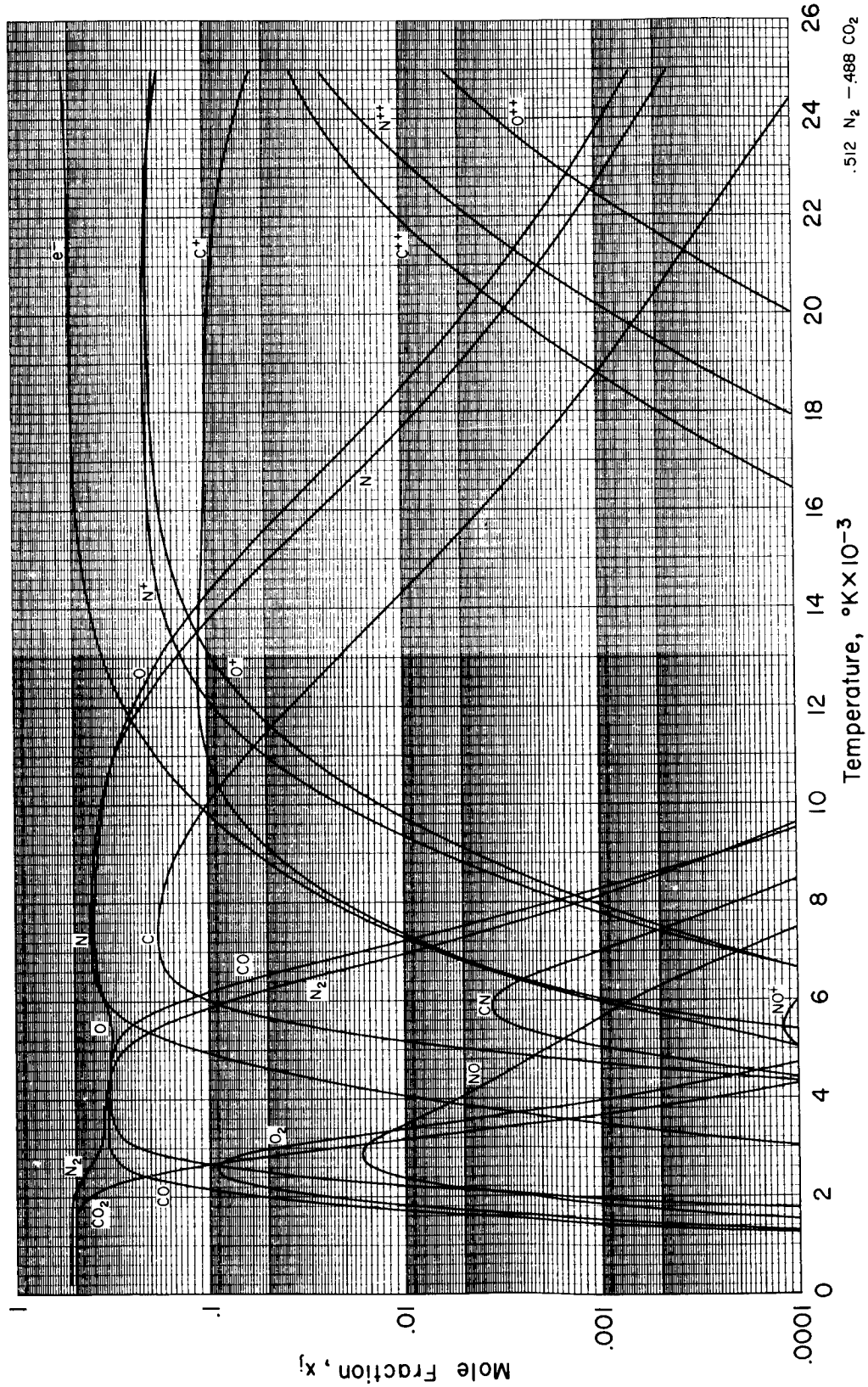
(e) $p/p_o = 10^{-1}$

Figure 21. - Continued.



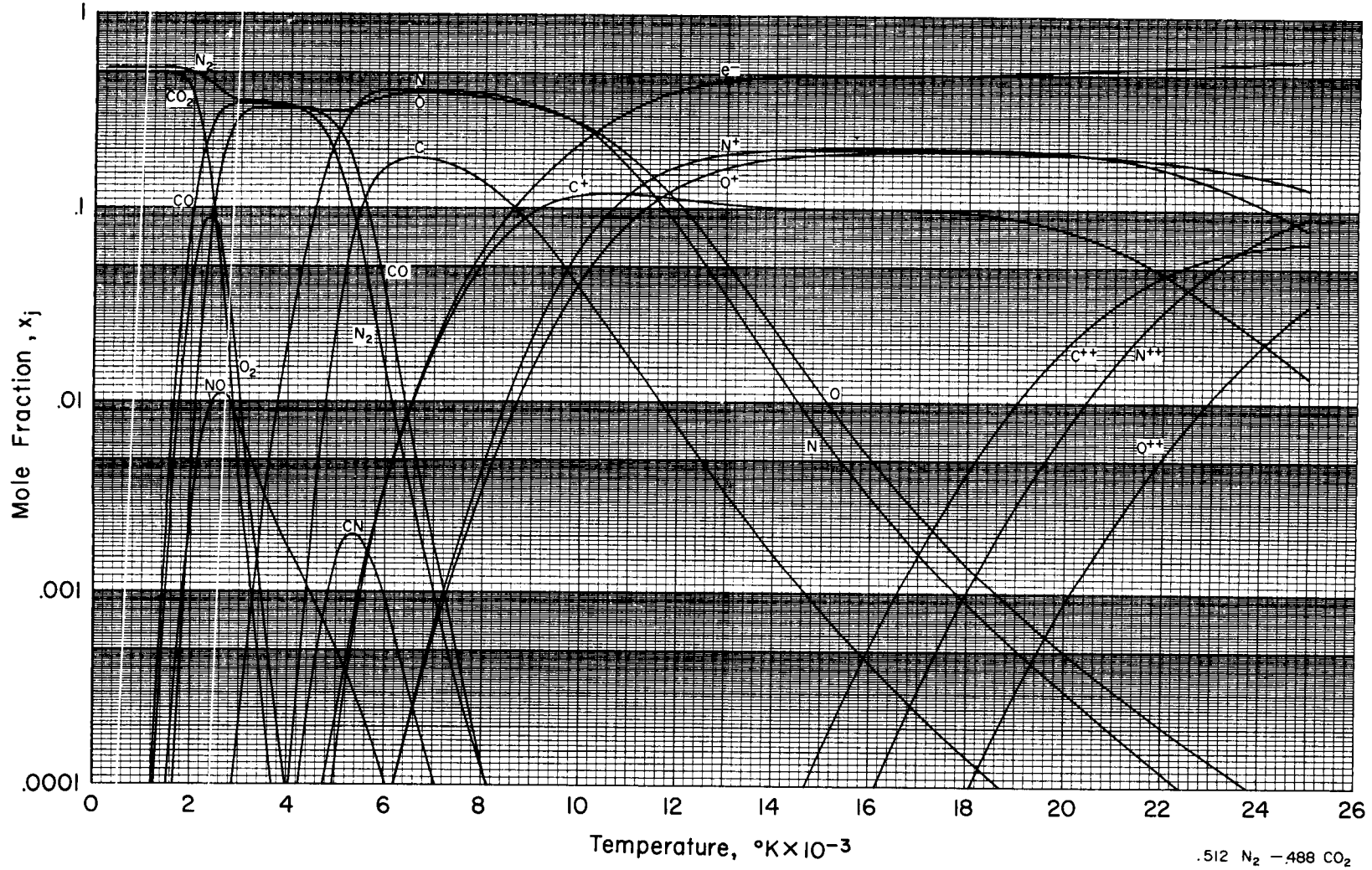
(f) $\rho/\rho_o = 10^{-2}$

Figure 21. - Continued.



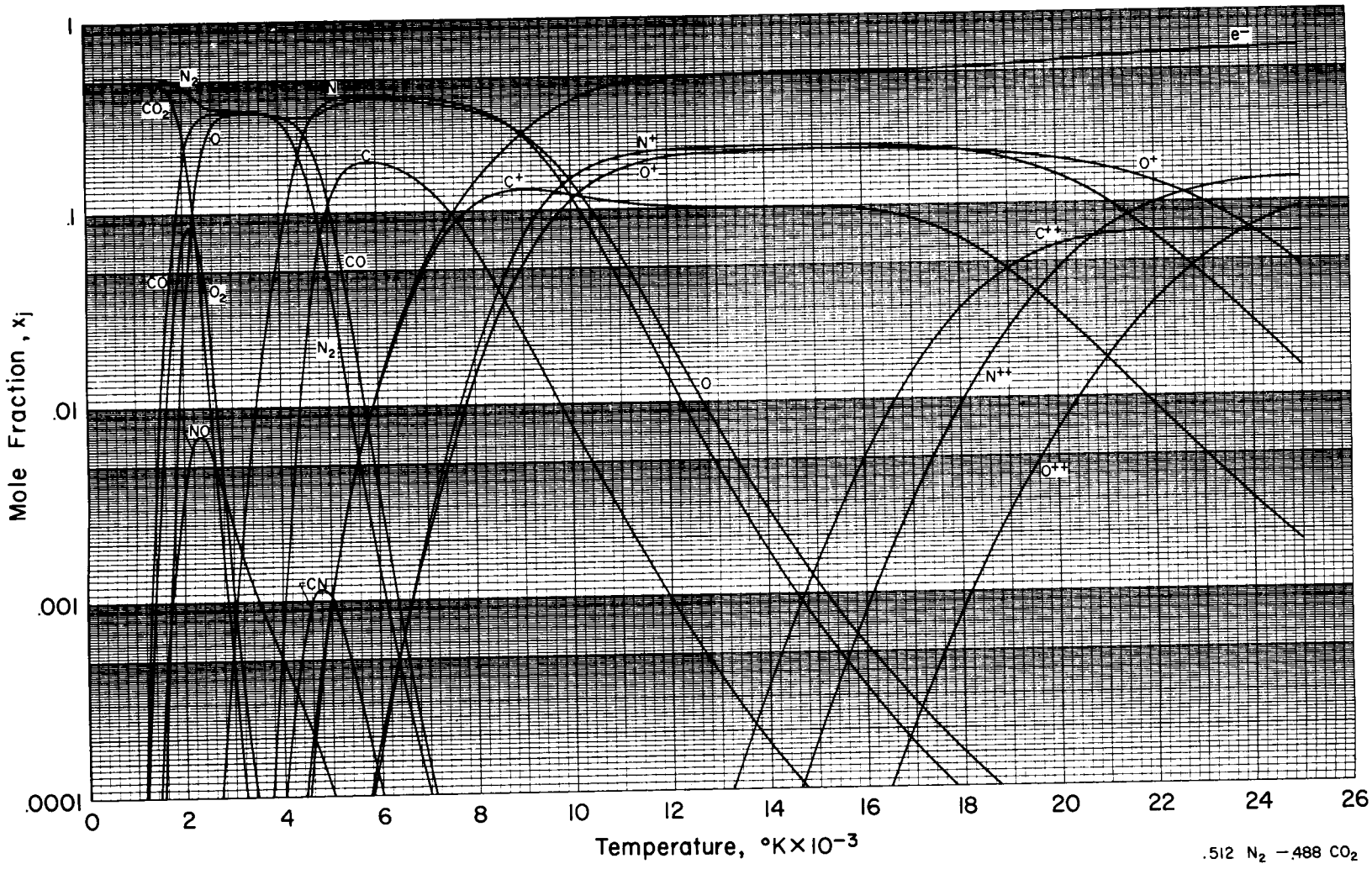
(g) $\rho/\rho_o = 10^{-3}$

Figure 21. - Continued.



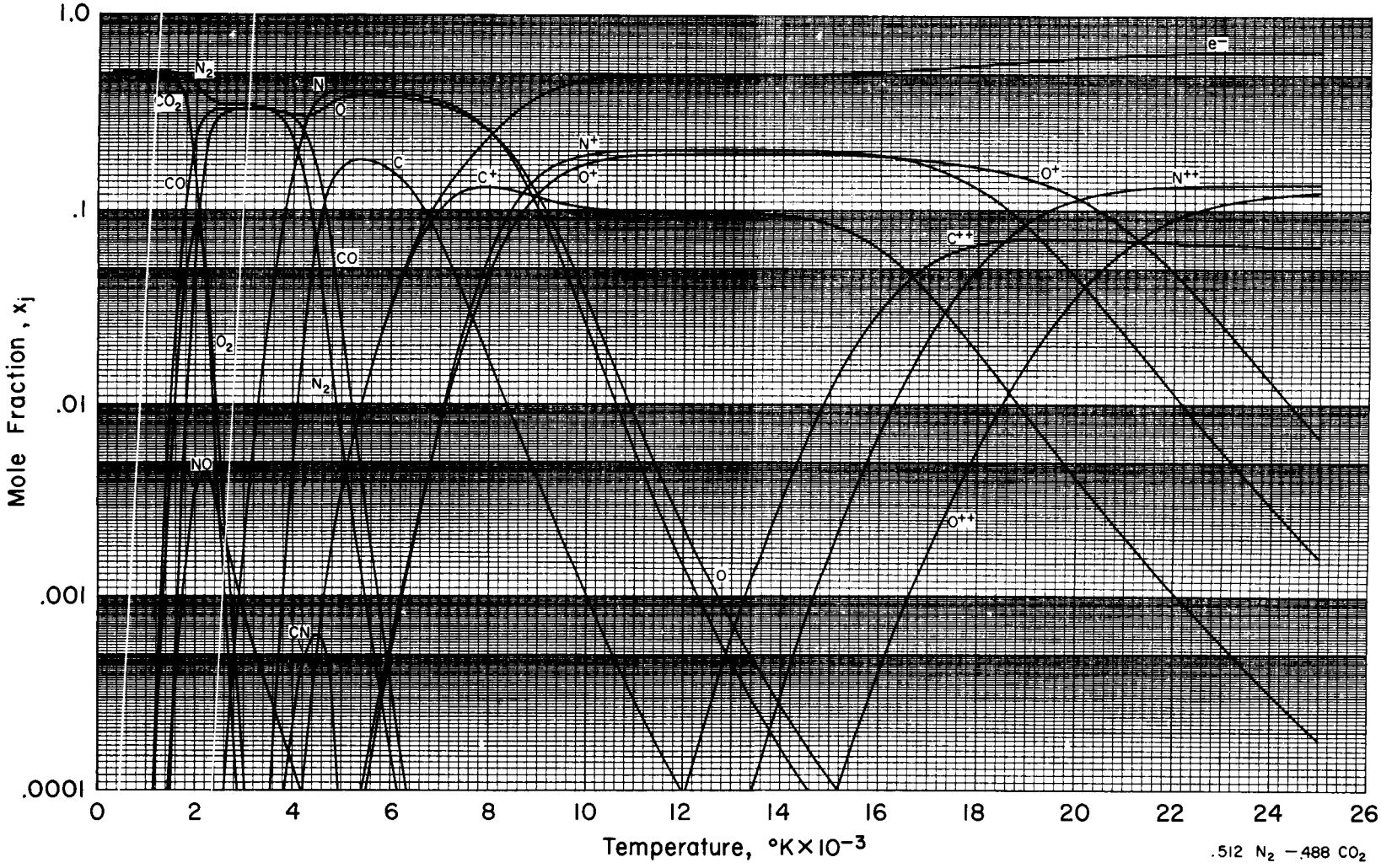
(h) $\rho/\rho_o = 10^{-4}$

Figure 21. - Continued.



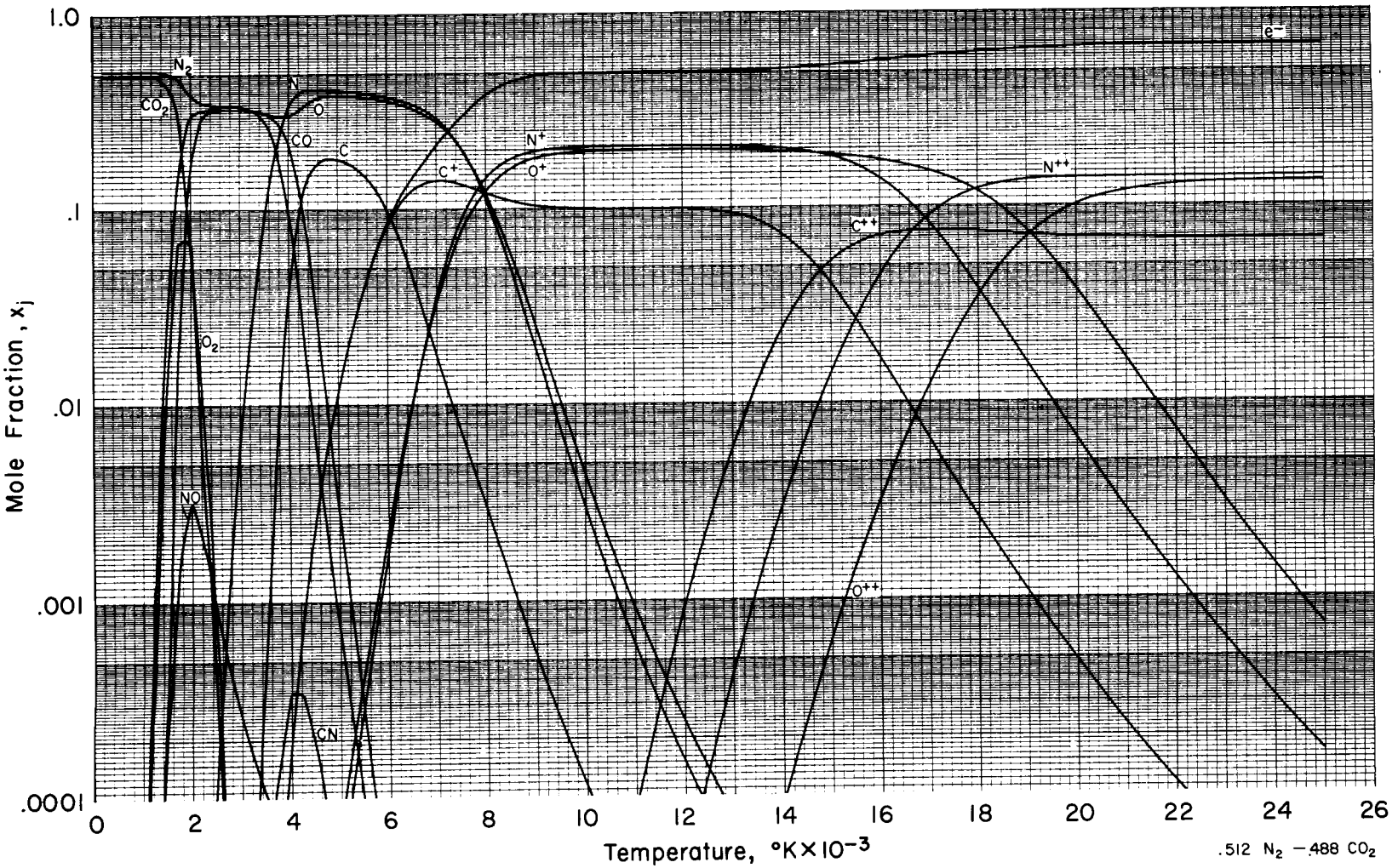
(i) $\rho/\rho_o = 10^{-5}$

Figure 21. - Continued.



(j) $\rho/\rho_o = 10^{-6}$

Figure 21. - Continued.



(k) $\rho/\rho_o = 10^{-7}$

Figure 21. - Concluded.

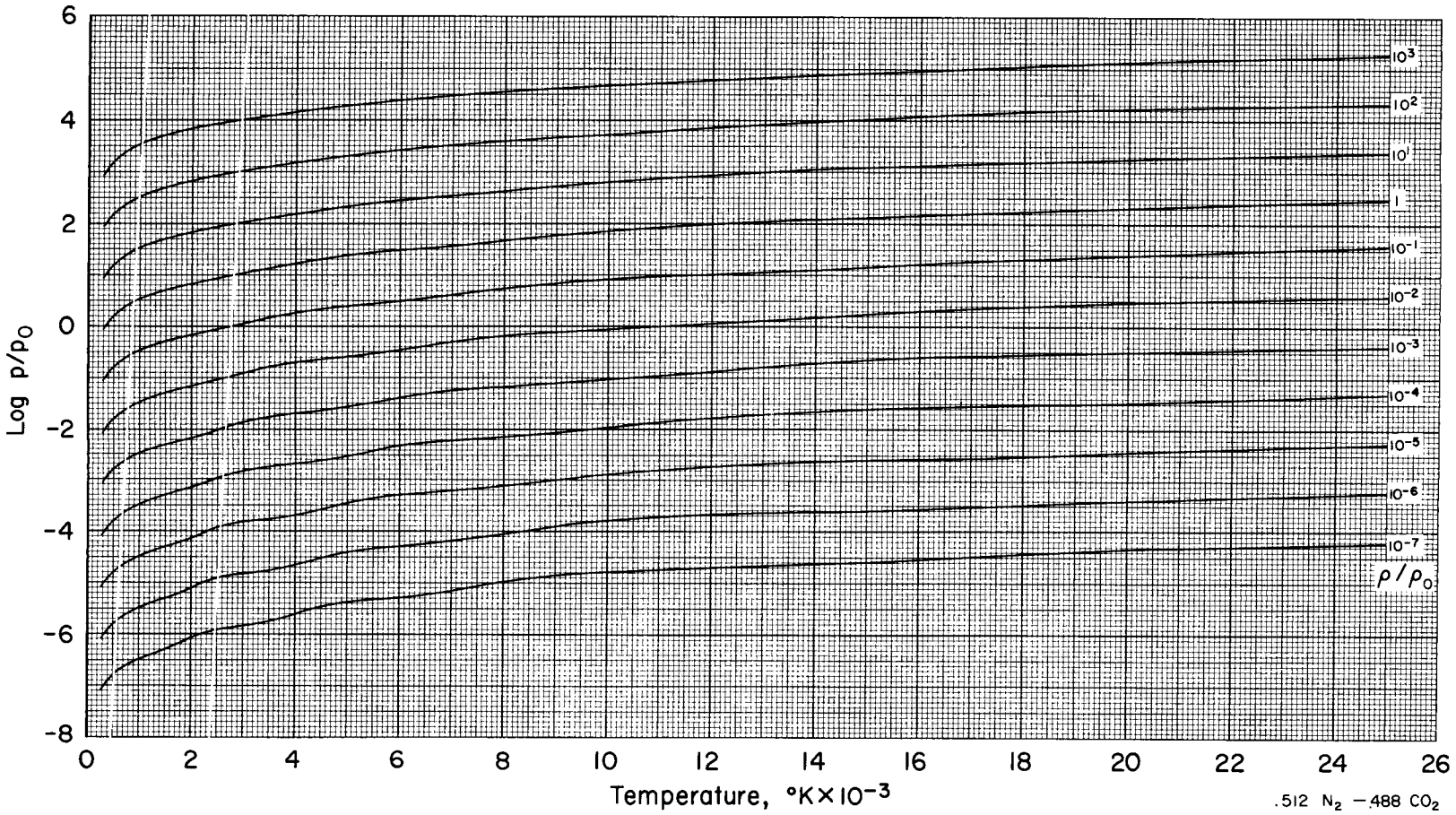


Figure 22. - Pressure as a function of temperature.

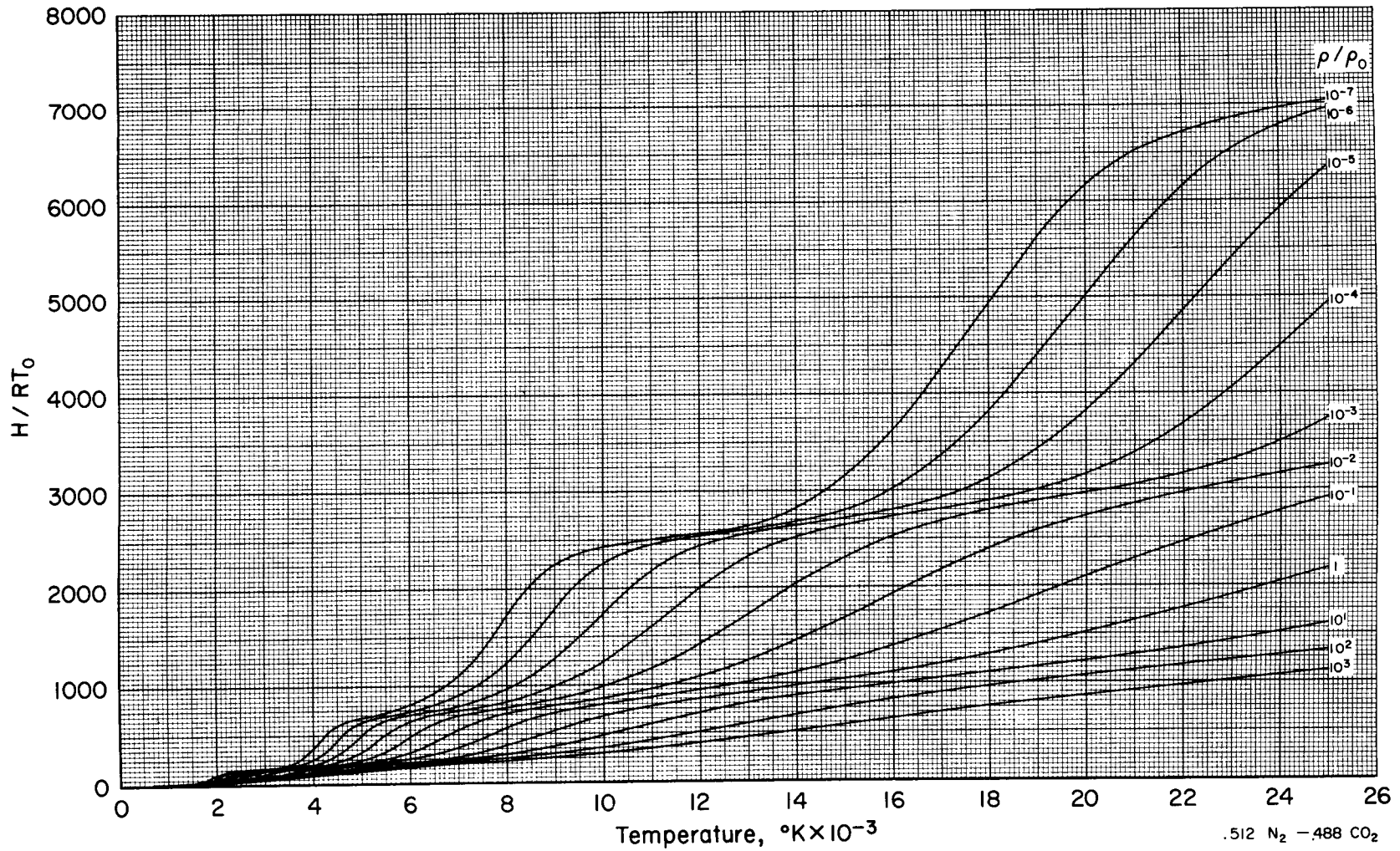


Figure 23. - Enthalpy as a function of temperature.

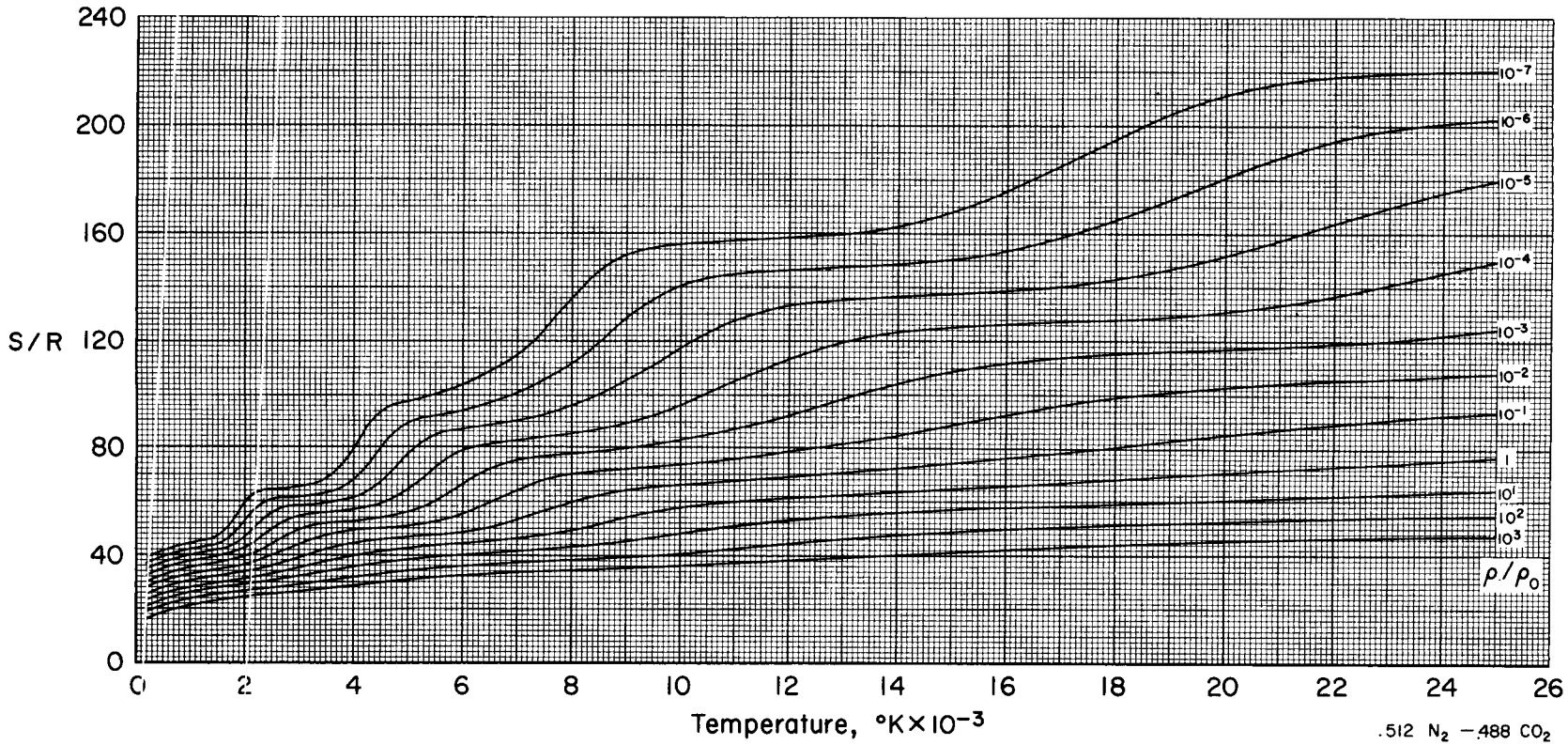


Figure 24. - Entropy as a function of temperature.

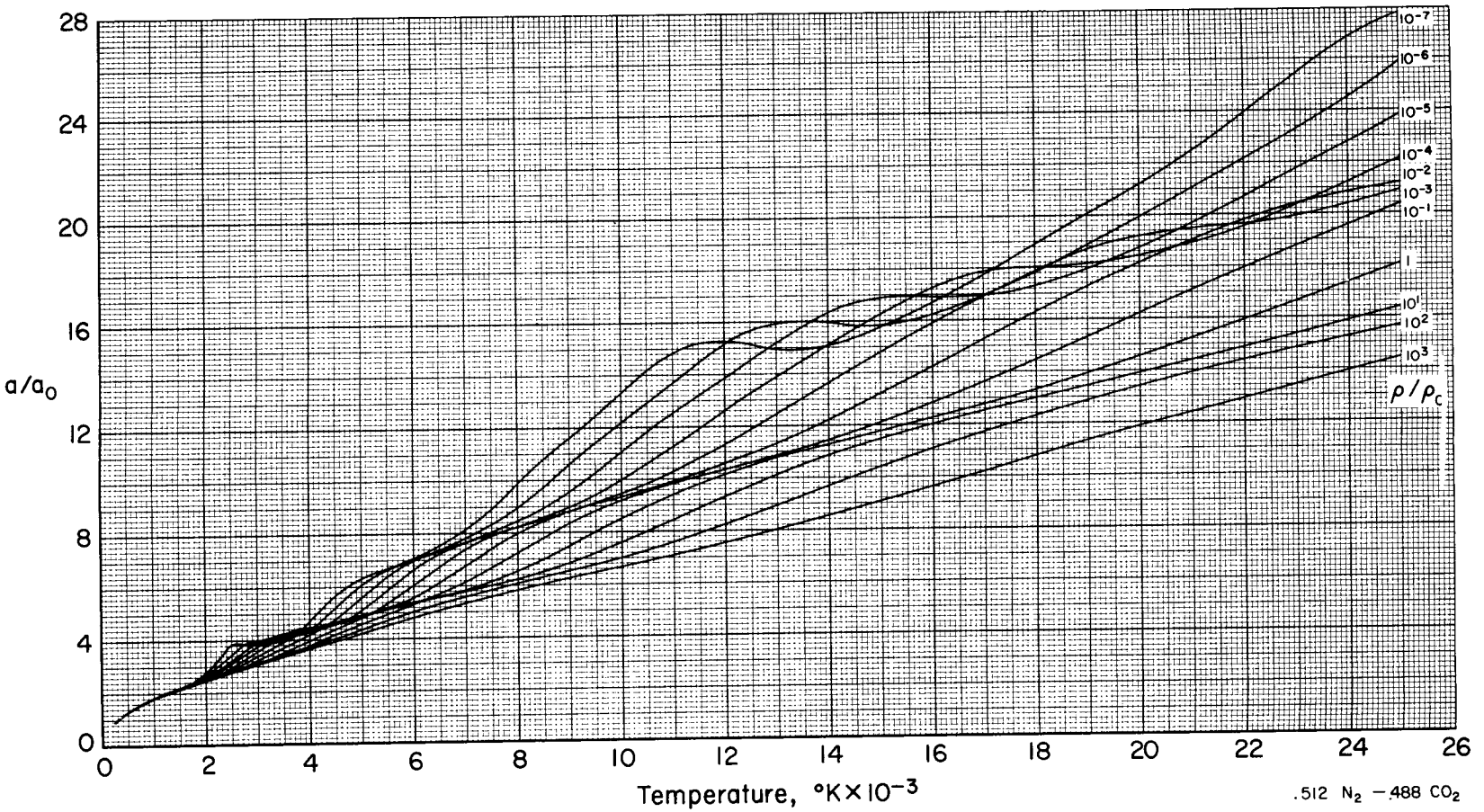


Figure 25. - Sound speed as a function of temperature.

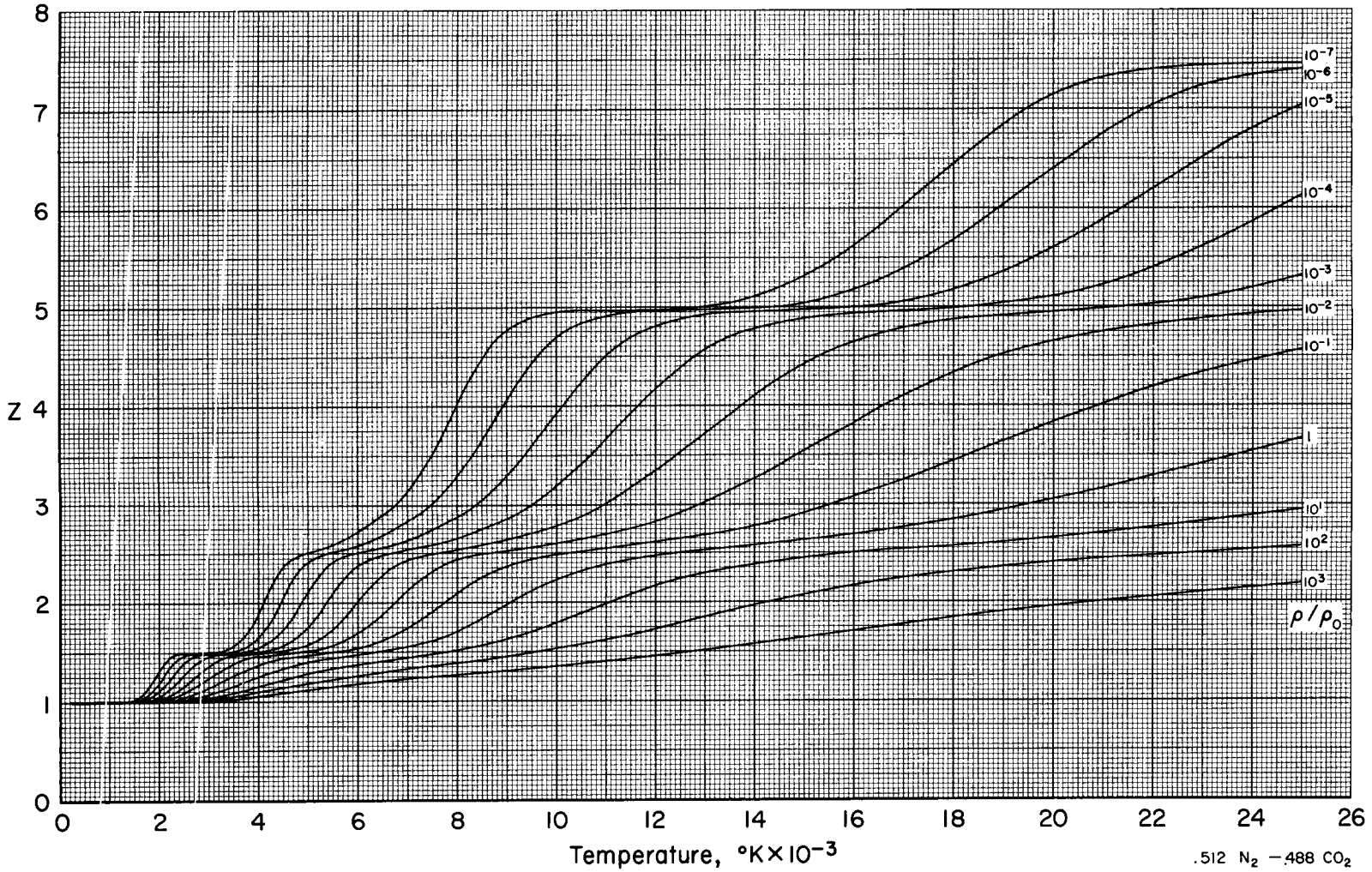
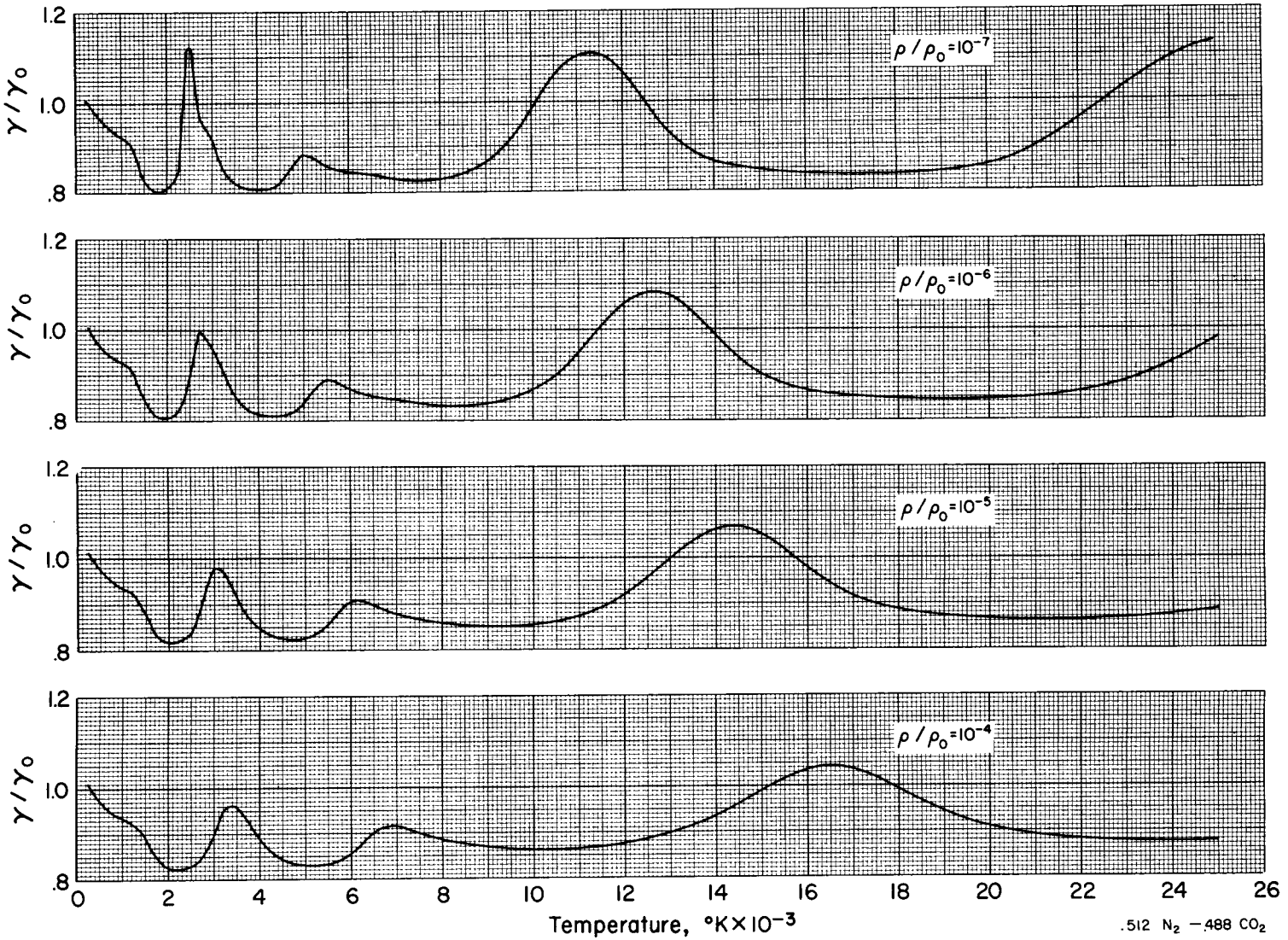
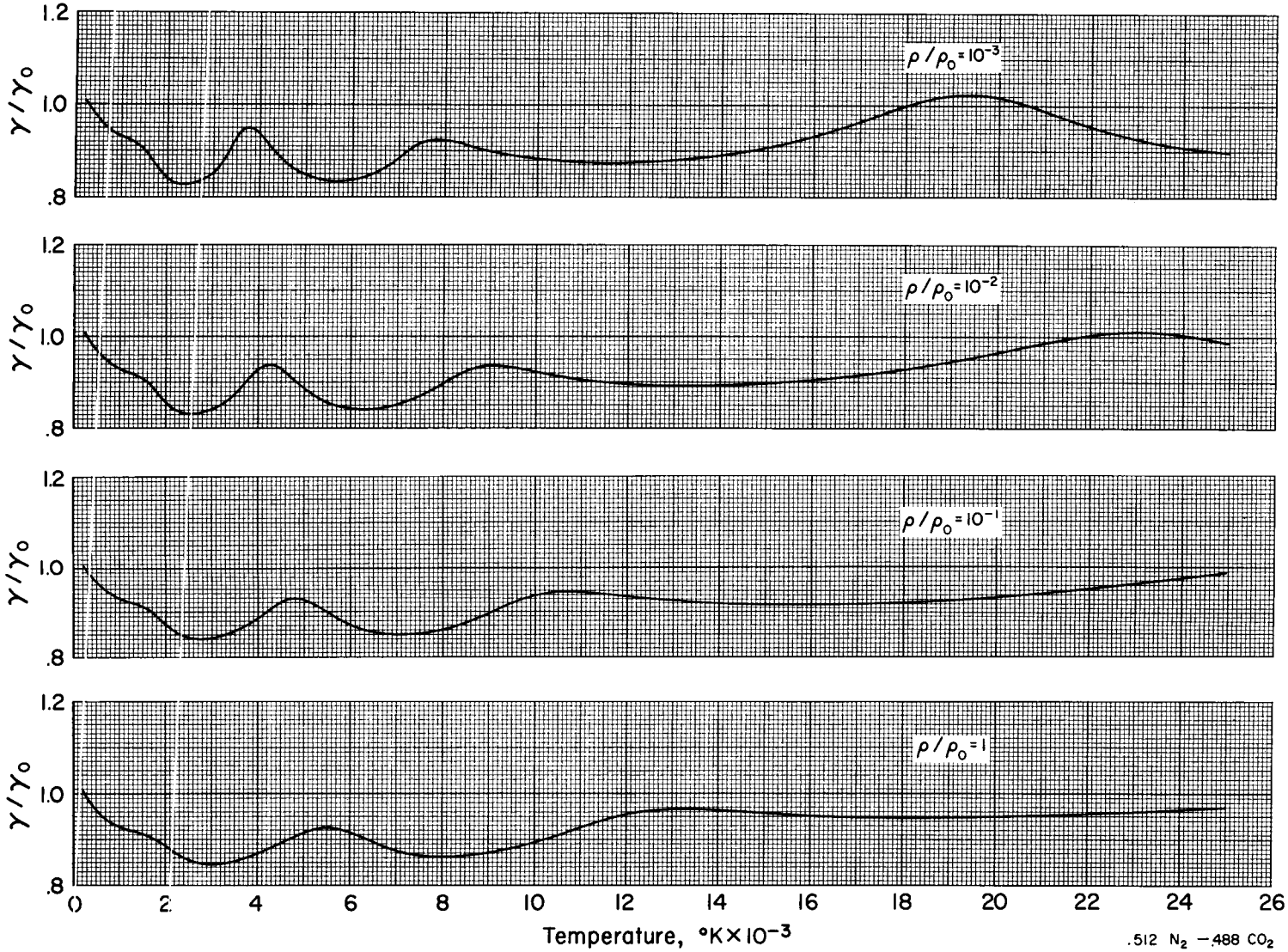


Figure 26. - Compressibility factor as a function of temperature.



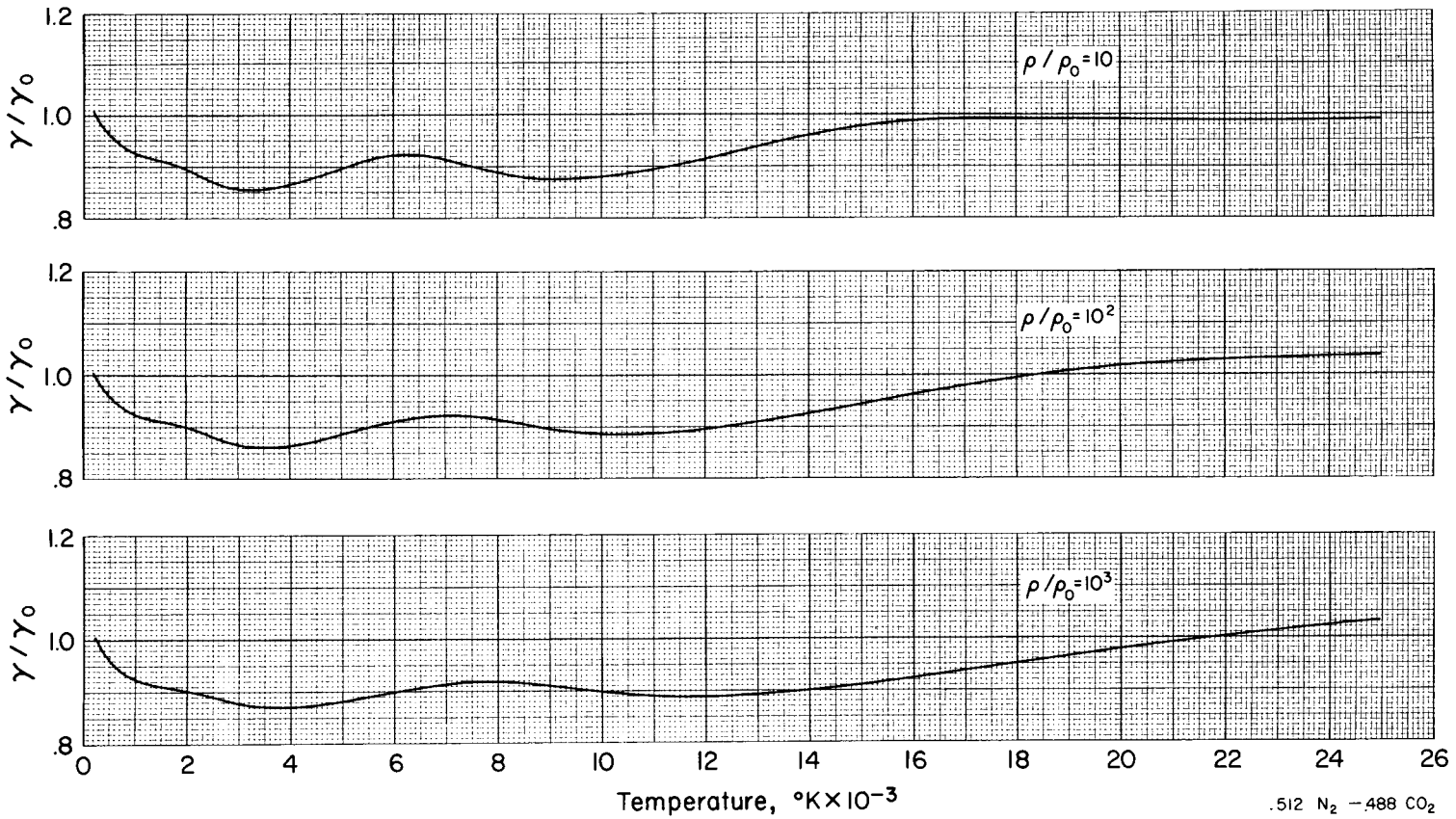
(a) $\rho/\rho_0 = 10^{-7}$ to 10^{-4}; $\gamma_0 = 1.332$

Figure 27. - Isentropic exponent as a function of temperature.



(b) $\rho/\rho_0 = 10^{-3}$ to 1; $\gamma_0 = 1.332$

Figure 27. - Continued.



(c) $\rho/\rho_o = 10$ to 10^3; $\gamma_o = 1.332$

Figure 27. - Concluded.

N65-35792

ERRATA

NASA SP-3021, 1965

EQUILIBRIUM THERMODYNAMIC PROPERTIES OF THREE ENGINEERING MODELS OF THE MARTIAN ATMOSPHERE

By Harry E. Bailey

Page 12

Change $RT_o = 0.3664 \times 10^5$ cal/g

to $RT_o = 0.1884 \times 10^2$ cal/g

Change $RT_o = 1.5331 \times 10^8$ J/kg

to $RT_o = 0.7884 \times 10^5$ J/kg

Page 13

Change $RT_o = 0.3548 \times 10^5$ cal/g

to $RT_o = 0.1827 \times 10^2$ cal/g

Change $RT_o = 1.4844 \times 10^8$ J/kg

to $RT_o = 0.7634 \times 10^5$ J/kg

Page 14

Change $RT_o = 0.2946 \times 10^5$ cal/g

to $RT_o = 0.1514 \times 10^2$ cal/g

Change $RT_o = 1.2324 \times 10^8$ J/kg

to $RT_o = 0.6338 \times 10^5$ J/kg

NASA-Langley, 1968 A-2107

Issued 5-24-68